PROJECT SQUID

SEMI-ANNUAL PROGRESS REPORT

OCTOBER 1, 1953

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Project SQUID is a cooperative program of basic research in Jet Propulsion. It is supported jointly by the United States Army, Navy, and Air Force and is administered by the Office of Naval Research through contract N6-ori-105, Task Order 111 NR-098-038.

November 12, 1953

To: Project SQUID Distribution List

From: Project SQUID Headquarters

Subject: "Wave Diagrams For Nonsteady Flow in Ducts" by Dr. George Rudinger

In connection with his work under a Project SQUID contract at Cornell Aeronautical Laboratory, Dr. George Rudinger has prepared a treatise on the construction and use of wave diagrams for the solution of problems in unsteady flow. This volume is essentially a handbook of procedures for carrying out graphical and numerical calculations by the so-called method of characteristics. It also serves as an introduction to the field of nonsteady flow phenomena.

In accordance with its custom of publishing all results of the scientific investigations which it sponsors, Project SQUID is planning to make copies of Dr. Rudinger's work available to those on its regular distribution list. This book will be much larger, and therefore more expensive, than the usual report or reprint. Moreover, it deals with a highly specialized field of interest. In order to avoid unnecessary expense, it is desired to send copies only to those who definitely need and want them.

Therefore, if you wish to receive this book, will you notify this office by letter not later than January 1, 1954. Failure to indicate your desire by that date will be interpreted as meaning that you do not wish to obtain a copy. In this connection, I should like to point out that arrangements are being undertaken to have the book printed by a commercial publisher. Consequently, it will be possible to purchase copies at a later date.

This notice is being sent to all those on the regular SQUID mailing list.

Sincerely yours,

John B. Fenn

John B. Fenn
Director

JBF/bs

SEMI-ANNUAL PROGRESS REPORT

PROJECT SQUID

A COOPERATIVE PROGRAM
OF FUNDAMENTAL RESEARCH
AS RELATED TO JET PROPULSION
FOR THE
OFFICE OF NAVAL RESEARCH, DEPARTMENT OF THE NAVY
RESEARCH AND DEVELOPMENT COMMAND, DEPARTMENT OF THE AIR FORCE,
AND THE
OFFICE OF ORDNANCE RESEARCH, DEPARTMENT OF THE ARMY

This Report covers the unclassified work accomplished during the period 1 April, 1953 to 30 September, 1953 by prime and subcontractors under contract number N6-ori-105, Task Order III, NR-098-038.

JAMES FORRESTAL RESEARCH CENTER
PRINCETON UNIVERSITY

October 1, 1953

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MIXING OF SUPERSONIC AND SUBSONIC GAS STREAMS

Princeton University - Phase 8

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I. Glassman, W.R. Warren, Jr., E.T. Pitkin

Introduction

The study undertaken in this phase is concerned with the transfer processes associated with supersonic mixing and the aerochemical effects on these transfer processes. The first portion of this work has been concerned with the investigation of axial symmetric parallel-flow supersonic jets issuing into free air. These investigations, while evaluating the nozzles designed for use in dual stream mixing, will also supply pertinent data on free jet mixing. Mixing data on free compressible jets are extremely sparse.

Discussion

The experimental evaluation of the M-2.6 nozzle issuing into free air has been completed and work is now proceeding with the M-1.5 nozzle. Schlieren photographs were taken of the M-2.6 discharge as well as total and static pressure profiles at downstream positions of 0, 1-2/3, 5, 10, 12-1/2, 15 and 20 exit diameters. The weak shock waves which occurred at the nozzle exit were found not to affect the mixing to any appreciable extent. The presence of these waves was discussed in the last progress report.

The nozzle under consideration has a 1.47 inch throat diameter and a 2.55 inch exit diameter. The stagnation temperature of the supersonic stream was consistently 11°R lower than ambient temperature and averaged 527°R. From the experimental data there have been calculated velocity, Mach number and momentum profiles at each downstream position. The half velocity line ($u/u_c = 1/2$, where u is the point velocity and u_c is the velocity at center line of the jet) in the mixing region of the jet formed an angle of 5 degrees with the jet axis. This result is about the same as that obtained by previous investigators of low speed jets (1). The length of the potential core of undisturbed velocity was 12-1/2 diameters. As is to be expected, this value is substantially larger than those reported by previous investigators of low speed jets (1,2,3). The length of the potential core is most likely a function of the initial density ratio in free jet studies. The de-

tails of this experimental work will be presented in a technical report being prepared for publication.

A semi-empirical theory has been developed for predicting the length of potential core, velocity decay on axis, the boundaries, and the velocity at any point of a supersonic air jet exhausting into air at rest.

The integrated axial momentum equation is employed as the basic equation in the analysis. The use of the integrated equations is one of the general procedures in analyses dealing with spreading of jets (4). A new approximate expression for the density variation is chosen in order to simplify the solution when the integrated equations include compressibility parameters. This approximation assumes the density at any point in the jet is a particular function of the local mean velocity and constant quantities only. Because it is believed not to be valid in compressible flow, the usual Prandtl representation of shear stress (5) is discarded and a somewhat simpler form similar to that suggested by Reichardt (6) is used.

This new analysis shows good correlation with the heated jet data of Pabst (3) and the high velocity data discussed above. The complete analysis and comparisons with experimental data will be presented in a manuscript also being prepared for publication.

Notes and References

1. Kuchemann, D., and Weber, J., "Aerodynamics of Propulsion", McGraw-Hill, New York, 1953, pp. 235-239.

2. Forstall, Jr., W., and Shapiro, A. H., "Momentum and Mass Transfer in Coaxial Gas Jets", Journal of Applied Mechanics, 17, p. 399, 1950.

3. Pabst, O., "Die Ausbreitung heisser Gasstrahlen in bewegter Luft", Deut. Luftfahrtforshung U.M. Nos. 8004 and 8007, 1944 (Translation from Document Service Center, ASTIA, ATI Nos. 45861 and 3124).

4. Squire, H. B., and Trouncer, J., "Round Jets in a General Stream", British ARC Rept. and Mem. No. 1974, 1944.

5. Goldstein, S., "Modern Developments in Fluid Dynamics", Vol. I, Oxford, 1938, p. 206.

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FUNDAMENTAL INVESTIGATION OF NONSTATIONARY FLOW PHENOMENA

Cornell Aeronautical Laboratory, Inc. - Phase 1

G. Rudinger, Phase Leader
H. Glick, A. Hertzberg, W. Squire
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Introduction

This study is concerned with the extension of theoretical and experimental methods for the analysis of nonsteady-flow problems. Theoretical work is based mainly on the method of characteristics and the procedures of this method have been collected in a systematic manner for publication in book form. Boundary conditions in nonsteady flow are studied experimentally by means of shock tubes. Shock tube techniques are also being developed for the study of the kinetics of chemical reactions.

Discussion

(a) Handbook of Procedures for Nonsteady Flow. The differential equations for quasi-one-dimensional nonsteady flow cannot be solved in a general form except in cases of extreme simplicity. The graphical-numerical method of characteristics is generally employed to obtain solutions for specific problems. This method has been extensively used at Cornell Aeronautical Laboratory for several years and considerable experience has been gained in the handling of a great variety of problems. For efficient application of the method, the operator must, however, have a knowledge of numerous procedures that are required for the various cases of wave interactions, boundary conditions, and so forth. A manual of these procedures has been prepared in which particular stress is placed on the practical aspects of wave diagram construction. The completed manuscript has been sent to the D. Van Nostrand Company for publication in book form.

(b) Use of I.B.M. Equipment for the Calculation of Wave Diagrams. The graphical-numerical procedures to solve problems of nonsteady, quasi-one-dimensional flow (see (a) above) are rather time consuming. An attempt was made to carry out the calculations with the aid of I.B.M. equipment (1). Although the individual procedures are not too difficult for the machines to handle, there exists a great variety of them and the difficulty consists in providing the machines with adequate methods of judging which procedure

to select at any point. This problem becomes clear when it is realized that one must be able to deal with discontinuities - such as shock waves or contact surfaces - whose location and even existence in the wave diagram are not known beforehand. Since the most convenient procedures for manual computations are not necessarily also best for digital calculators, a number of alternative procedures were investigated.

Eventually, it became apparent that, regardless of the procedures used, most of the machine time would be required to "judge" which problem has to be solved at any point of the wave diagram. Since in manual operation no time is lost for such judgements, the advantage of the machine to be able to calculate faster than a human operator is largely lost again. In the final analysis, the conclusion was reached that the I.B.M. equipment of the Laboratory (a card-programmed calculator) would not offer any advantages over the present manual method of computing.

Use of the new #701 calculator in New York City was also considered, but it was concluded that the extremely high cost of its operation makes it impractical to use.

In view of these findings, no further work on this problem is being planned at the present time.

(c) <u>Boundary Conditions in Nonsteady Flow</u>. In the course of wave diagram construction, the conditions that govern the reflection of waves from boundaries must be known. In the case of open ends of a duct, the waves

pass through the "boundary" and create a nonsteady external flow field. The boundary conditions should be represented by the fact that the internal and external flows must be identical at their junction but because of the extreme difficulties of analyzing three-dimensional wave phenomena, the rigorous matching of the two flow fields may be replaced by approximate boundary conditions. The propagation of waves beyond the end of the duct is then fully implied in the assumed conditions. Customarily, one treats the flow as quasi-steady and applies the steady-flow boundary conditions. The purpose of this study is to determine to what extent such approximations are satisfactory and, if necessary, to establish more accurate "effective" boundary conditions.

The problem that is being studied at present is the reflection of shock waves from an open end of a duct. The original experiments (2) which were carried out in a small shock tube (square cross section of about 1 square inch) have been continued with a larger round tube of 3 inches diameter. As expected, the friction effects that were disturbing in the small tube are now effectively eliminated. The former, qualitative findings were confirmed. During the passage of the reflected expansion wave, the pressure drops a little slower than predicted from the quasi-steady-flow boundary conditions. The weak compression pulse that followed the expansion wave (2) was again noted, but its magnitude for all shock strengths is so small that its practical significance is doubtful.

In the course of the experiments, it was found that the calibration of the pressure gauge drifted considerably and only a limited number of the data

are, therefore, reliable enough for quantitative evaluation. By measuring the velocity of the initial shock wave (timing between two stations) it will be possible, in the future, to check the calibration for every run.

For extremely weak shocks, the boundary conditions could be determined theoretically on the basis of acoustic theory. Good agreement was found between these theoretical results and the limited experimental data available. It has not yet been established at what shock strength the acoustic theory becomes inadequate.

A dimensional analysis of the problem of shock reflection from an open end was undertaken and it appears that it should be possible to obtain fairly simple effective boundary conditions from this investigation.

After completion of the problem of shock reflection from an open end, it is planned to extend the investigation to other boundary conditions.

(d) Nonsteady Flows with Spherical or Cylindrical Symmetry. The usual methods of wave diagram construction for one-dimensional flow are easily extended to flows with cylindrical or spherical symmetry by letting the "duct area" increase proportional to the distance or the square of the distance from the center of symmetry, respectively. However, the method breaks down at the center of symmetry and a solution in the vicinity of this singularity is sought.

Various attempts to obtain approximate solutions to this problem were made and a tentative procedure has been worked out. It will be necessary to prepare some wave diagrams to test the usefulness of this approach.

(e) Use of Shock Tube Techniques for the Study of the Kinetics of Chemical Reactions. The conventional shock tube produces a series of pulses of decreasing pressure and temperature amplitude as the waves are reflected back and forth in the tube. A simple way of eliminating all but the first pulse was described previously (3). Construction of the shock tube has been completed. Some time was spent to develop reliable methods of diaphragm breaking since two diaphragms must be ruptured with accurate timing. Eventually, the following system was chosen: Each diaphragm is punctured by a needle that is driven by suddenly increasing the pressure on a piston connected with it. This sudden pressure rise is produced by connecting the ducts in which the pistons move to a small auxiliary shock tube; by making the ducts of unequal length, the time between breaking of the diaphragms can be controlled. Preliminary experiments indicated that the time interval between the breaking of the diaphragms should be reproducible to within about 0.1 millisecond. Experiments will start with a study of the formation of NO in air.

Some consideration was also given to the possibility of using shock tube techniques to obtain the heat of dissociation of nitrogen for which several distinctly different values have been obtained by means of other techniques (4). It seems feasible to measure the flow velocity and the speed of sound behind

a strong shock wave by observing optically the propagation of small disturbances. This information can also be computed from the known strength of the primary shock wave for various values of the heat of dissociation, and comparison of theoretical and experimental results should yield the value of the heat of dissociation. It is planned to check the experimental technique by making observations first in oxygen for which the heat of dissociation is accurately known.

Notes and References

1. This part of the work was carried out in cooperation with Mr. D.Feigenbaum and Dr. D. Orloff from the I.B.M. Section of this Laboratory.
2. Project SQUID Semi-Annual Progress Report, April 1, 1953, p. 9.
3. Project SQUID Semi-Annual Progress Report, October 1, 1952, p. 14.
4. A. G. Gaydon, Dissociation Energies and Spectra of Diatomic Molecules. Chapman and Hall, Ltd., London, 1947.

INVESTIGATION OF TURBULENCE

Johns Hopkins University - Phase 1

Leslie S.G. Kovasznay - Phase Leader

Introduction

The Department of Aeronautics is pursuing a long range research program to investigate turbulence in general and turbulent phenomena occurring in high speed flows in particular. The program is jointly sponsored by Project SQUID and the Navy Bureau of Ordnance. The research work during the last period has been concerned with several distinct problems:

(1) Hot-wire measurements in the supersonic turbulent boundary layer.

(2) Ultrasonic experiments.

(3) Various types of correlations in the theory of asymmetric turbulence.

(4) Interaction of weak fluctuations with a strong shock wave.

Problems (1) and (2) are experimental in nature, (3) and (4) are

theoretical analyses.

Discussion

(1) Hot-Wire Measurements in the Supersonic Turbulent Boundary Layer. The preliminary results of this work have been reported in the previous progress report. The completed work has been submitted for publication and will shortly appear (1).

The major conclusions of this long range theoretical and experimental program are the following:

(A) Random fluctuations in a supersonic flow can be decomposed into three distinct modes: vorticity, sound, entropy. The modes obey separate linear differential equations if the fields are weak and have moderate interaction if the fields are stronger.

(B) If the spatial scale of the disturbances is not too small, the effect of viscosity and heat transfer can be neglected for the short time history of the disturbances, and the velocity, pressure and temperature fields can be easily split into the three modes: The velocity field is split into a solenoidal and an irrotational field. The former constitutes the vorticity mode; the latter belongs to the sound waves. The pressure fluctuations are split into isentropic fluctuations that belong to the sound wave mode and into a non-isentropic part that constitutes the entropy

mode. The vorticity mode has no pressure, density or temperature fluctuations.

(C) The hot-wire anemometer can be operated successfully in a supersonic flow. The key to separation of the modes is the "fluctuation diagram" representing the r.m.s. output of a hot-wire at different operating wire temperatures.

(D) A variety of preliminary hot-wire measurements in supersonic wind tunnels indicate that all three modes are significant but their relative importance may vary from one flow region to another. Sound waves may have more relative importance in the "free stream" and the other two in shear layers (boundary layers, wakes). The entropy mode (temperature spottiness) was always significant when the vorticity mode (turbulent velocity fluctuations) was intense.

(E) The fluctuation field in a supersonic turbulent boundary layer appears quite similar to a low speed boundary layer. The only important difference is the intense temperature spottiness caused by the intense turbulent heat transfer across the layer.

(2) Ultrasonic Experiments. Since the ultransonics generated in air by barium titanate crystals were found to be too weak for feasible optical detection, a Hartmann ultrasonic generator was constructed to produce periodic disturbances in the neighborhood of 40 kC. When operating with a reservoir pressure of approximately 100 pounds, the output was sufficiently intense to permit optical detection with schlieren apparatus. The wave forms

obtained were found to be roughly sawtooth in nature rather than sinusoidal.

Future plans include the study of the propagation of weak waves through shocks and around solid boundaries.

(3) Various Types of Correlations in the Theory of Axysmmetric Turbulence. A theoretical study in two parts is being prepared. The first part, which is nearing completion, is concerned with kinematic and simple dynamic considerations of axisymmetric turbulence.

Instead of Chandrasekhar's "scalars" defining the various 1st, 2nd or 3rd order correlations, two types of correlations are introduced: (1) the vectors (velocities, for instance) are either parallel or perpendicular to the axis of symmetry; (2) they are either parallel or perpendicular to the vector between the two points. It is shown that the general correlations, in the tensor form, can be expressed as a function of these special types of correlations, and the relations between the "defining scalars" and these correlations, are derived. Similarly, new types of scales of turbulence, which are easier to handle, are introduced. It is found that the equation for the decay of kinetic energy is similar to the one for the isotropic case, provided the microscale is defined as before, but for a special configuration (55° angle). The relation between the triple correlations and the pressure velocity correlation is derived and the spectrum in the case of axisymmetry is discussed.

Next a study is made of the special case in which the axisymmetric field can be split up into two non-interacting fields, one of which is isotropic. After making certain assumptions, simpler characteristic relations between the correlations, the scales, and the microscale are derived. These results are checked against the classical results of the isotropic case.

The second part of this work will consist of a preliminary study of axisymmetric scalar fluctuations in the general case of axisymmetric turbulence and in the case of isotropic turbulence.

(4) Interaction of Weak Fluctuations with a Strong Shock. Previously, interaction between weak harmonic fluctuations (sound, vorticity, entropy spottiness) and a strong shock of infinite extent was investigated. The analysis is being extended to the experimentally more realistic configuration in which the shock is attached to a wedge. Besides the previous solution for the refracted waves, one has to deal with the waves reflecting from the wedge and their modification of the shock wave form and corresponding downstream modes of fluctuations. The system of differential equations and boundary conditions on the wedge and the shock wave can be satisfied formally by series leading to Neumann expansions at the boundaries. At present, difficulties in numerical computation due to slow convergence of the series are being investigated.

Future Plans

After having demonstrated that the three different modes of fluctuations do exist in a supersonic stream the attention shifted to the interaction of these modes with each other or with other flow phenomena.

There exists a strong suspicion, supported by some experimental indication, that sudden expansion damps and a sudden compression (shock) enhances turbulence. The strong nonlinearity present in a shock wave produces interaction between the modes (see (4) above), therefore it is a legitimate experimental objective to study turbulence (all three modes) passing through a shock wave or an expansion region.

The experiment contemplated is the interaction of a turbulent supersonic wake flow with a single plane oblique shock wave or oblique expansion fan. Measurements of mean quantities by conventional methods (pitot tube, thermocouple and fluctuations by the hot-wire anemometer is expected to yield:

(a) An experimental verification of interaction of fluctuation modes when passing through the shock wave.

(b) New understanding of the behavior of turbulence in accelerated or decelerated flows.

Reference

1. Leslie S. G. Kovasznay, "Turbulence in Supersonic Flow," Journal of the Aeronautical Science, October 1953.

TRANSPORT PROPERTIES OF LIQUIDS

Princeton University - Phase 6

Ernest F. Johnson, Phase Leader
William J. Scheffy, Paul E. Parisot

Introduction

This phase is concerned with developing useful generalizations for predicting the important molecular transport properties of liquids over wide ranges of temperature. In particular it is concerned with low molecular weight organic liquids which are of potential value as rocket fluids. Because of the lack of reliable data on which to base the generalizations, the main emphasis of effort has been on the design and construction of versatile apparatus for measuring these properties. Two properties are under study, thermal conductivity and viscosity. Both properties are important in the design of rocket engines, chemical reactors, and other devices.

Discussion

Problem 6R1 - Thermal Conductivities of Liquids. During the past period the assembly of the final apparatus for measuring thermal conductivities was completed. This apparatus consists of a series of concentric, long-tube, thin-walled metal cylinders confining the liquid in the thin annuli between the cylinders. A heater at the axis provides a radial flow of thermal energy which can be measured in steady-state by the temperature gradient across a cylindrical bed of sand surrounding the bomb which encloses the cylinders. By measuring the total drop in temperature across the cylinders which bound the liquid at known thermal fluxes it is possible to compute the thermal conductivity of the liquid.

Since the absolute accuracy of the liquid thermal conductivity measurement depends on how accurately the sand bed conductivity is known, a number of studies were made to determine not only the thermal conductivity of the sand but also the dependence of the conductivity on temperature, bed porosity, and moisture content. Several transient state methods of measurement proved unsatisfactory from the standpoint of attainable accuracy, and ultimately a steady-state method was developed which could give results with an accuracy of one per cent. This last method involved measuring the electrical energy input to a wire-wound heater mounted in the center of the sand bed and measuring the temperature gradients in the bed. It was found that the sand thermal conductivity varied two to four per cent depending on the moisture con-

tent and up to fifteen percent depending on how firmly the bed was compacted. Studies are in progress to show how well the moisture content and bed porosity can be controlled.

An alternate method for measuring the radial thermal transfer in the liquid thermal conductivity apparatus is to measure the electrical energy imput to the asial heater and make reasonable allowances for axial heat losses just as was done in the steady-state studies on the sand. The manipulation is somewhat more cumbersome, and the analysis of the longitudinal heat losses is more complex. In a demonstration of this method the thermal conductivity of air was measured at three different temperatures. The results agree with averaged values of previous observers (1) as shown in the table below.

Thermal Conductivity of Air Btu,ft./hr.deg.F.ft^2

Temperature	240°F.	360°	500°
Previous Data (average)	0.0190	0.0215	0.0250
Present Work	0.0190	0.0205	0.0233

Problem 6R2 - Viscosities of Liquids. Since viscosity and thermal conductivity can be related theoretically for simple systems, more powerful generalizations for predicting both in the absence of experimental data can be developed by treating them together. It is the purpose of this problem to investigate the viscosities of the liquids being studied in connection with Problem 6R1.

For reasons of convenience in manipulation it is desirable that a single apparatus be used for all the viscosity measurements and that each liquid be

studied over the full temperature range without having to open the apparatus. Since the temperature range is so wide, a twentyfold variation in viscosity must be accommodated. A survey of the literature has shown that only a capillary type viscometer, probably using a variety of tubes, can give reliable absolute values of viscosity over such a range.

The need for pressurizing the viscometer up to 1000 psi to prevent vaporization of the liquid sample seriously complicates the design.

In order to explore the various possibilities for successful design a modified Ostwald capillary viscometer has been constructed and operated on water. A variety of studies are in progress to identify practical operating procedures and design features.

Notes and References

1. L. M. K. Boelter and W. H. Sharp, "NACA Technical Note 1912", Washington, 1949.

HEAT CONDUCTIVITY OF GASES OVER A RANGE OF TEMPERATURES AND PRESSURES

Massachusetts Institute of Technology - Phase 2

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William T. Lindsay, Jr.
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Introduction

Reference is made to five prior reports dated April 1, 1951, October 1, 1951, April 1, 1952, October 1, 1952 and April 1, 1953. Three thermal conductivity installations have been in use, each specialised in design for the temperature range 90 to 300° K, 300 to 450, and 450 to 900. Measurements employing the older or middle range apparatus were discontinued last winter because of electrical insulation failure. The cell has not been reconstructed to date in view of the need for low temperature and high temperature measurements to complete the large amount of information accumulated in the range 300 to 450°.

The low temperature apparatus has been in continuous operation since April 1953 for measurements of the gaseous and liquid phases of the rare gases. Measurements for polyatomic gases will go forward during the coming winter.

The development of the high temperature apparatus has required sustained patience and experimental resource. Operation of the apparatus of the first design indicated improvements which were in progress as the April 1953 report was written. The redesigned system went into operation in June.

Discussion

The importance of the rare gas results relates largely to their importance in the statistical or kinetic theory of energy transport. Since the constant volume heat capacity or specific heat of a monatomic gas is independent of temperature, the ratio of the heat conductivity to the viscosity according to the present formulation of the dynamic theory of low pressure monatomic gases is temperature independent. In symbols, $\lambda / C_v \eta$, where λ denotes the heat conductivity, C_v the specific heat, and η the viscosity, should take a value close to 2.5. The observational material does indeed, as is well known, give a value about equal to the predicted. Our new measurements supplementing all reported values together with the

viscosity values reported when used to form the quantity $\lambda/C_v\eta$, designated F, indicate the following.

The data are numerous for helium, neon, and argon, and extend over a considerable range:- 1.6 to 600° K for helium, 90 to 600° K for neon and argon. In each case the value of F decreases with increasing temperature. The value 2.5 at room temperature diminishes to roughly 2.4 at 500° K for helium, 2.4 at 1000° K for neon, and 2.4 at about 1700° K for argon by extrapolation. The data for krypton and xenon are much too inconstant and limited in range to warrant comment on the trend of F.

New measurements have been made on neon and argon, gas and liquid phases (April 1953 Report). Ample supplies of pure krypton and xenon have been made available for measurements of the liquid and gaseous phases through the kindness of the Linde Air Products Company. The provisional data for argon follows.

Argon

Gas

T° K	P atm.	$10^5\lambda$ (cal/cm·sec·deg)
104.8	1.0	1.597
130.6	1.0	1.981
178.5	4.6	2.691
178.5	2.9	2.677
178.5	1.0	2.659
179.5	1.0	2.679
273.2	11.0	3.953
273.2	7.7	3.927
273.2	4.6	3.895
273.2	1.0	3.874

Liquid

T° K	P atm.	$10^5\lambda$ (cal/cm·sec·deg)
86.9	10.2	28.0
86.9	2.2	27.8
99.4	10.2	24.8
99.4	4.5	24.7
111.9	10.2	21.4

The temperature-pressure dependence of the conductivity of the gas may be represented, within the precision of the measurements, by the equation

$$\lambda = \frac{.3555 \times 10^{-5} \sqrt{T}}{1 + (146/T)\, 10^{-3/T}} \left(1 + 0.6\ ^{P}/_{T}\right)$$

where P represents the pressure in atmospheres
T represents the absolute temperature.

The high temperature equipment changes were as follows:

(1) The emitter heater originally consisted of a length of platinum-rhodium wire supported and insulated by three 2-inch porcelain rods within the platinum emitter tube. The potential leads were taken from each end of the mid-portion for measurement of power input.

The improvement consisted in the provision of heaters or heat stations at each side of the 2-inch mid-portion of the emitter. New porcelain rods were secured having a central 0.4 mm hole and four equally spaced 0.2 mm holes parallel with and equidistant from the center hole. The heaters are of 0.1 mm platinum-10% rhodium wire passed down and back in each end of the porcelain rod through a pair of diametrically opposed 0.2 mm holes. The center emitter heater is of 0.15 mm wire entering through the center hole of one end rod, and laced up and down through all five holes of the center mid-section rod, leaving the emitter through the center hole opposite from the one through which it entered. The entire assembly was set inside the platinum heater cylinder with alundum cement. Improvement in temperature uniformity was secured and a lessened temperature difference resulted between the heating wire and the outer surface of the emitter.

(2) The 0.1 mm thermocouple wire tested by the National Bureau of Standards indicated inhomogeneity and was replaced by 0.2 mm wire which our tests showed was much more resistant to alteration of electrical properties through cold working subsequent to annealing. The 0.2 mm wire was sent to the Bureau for calibration after tests for homogeneity.

(3) The mode of suspension of the wires in the cell was changed to eliminate strains which proved hampering in the case of the finer wire. The weight of the wires and insulations are taken by the "vicor" tubes which extend from the cell to each end of the quartz cell tube.

(4) A variety of other alterations and improvements were made of which the following are examples.

(a) The electrical shield was extended through the furnace using a 0.01 inch wall nickel tube.

(b) Pressure tight seals for wires emerging from the cell were made using teflon similar in design to the high pressure used in the intermediate temperature range cell.

(c) Electrical circuits were completely rewired using every known care in shielding and grounding. A new arrangement of voltage dividers was also installed and calibrated.

(d) The temperature control and regulating equipment was greatly improved as a consequence of operational experience.

(e) Auxiliary apparatus, for example, the gas-handling system was completed in a durable and convenient design.

Tests on the improved cell followed by measurements were begun in early June, as follows:

(1) Blank runs at 160, 450 and 700° C.

(2) Air runs at the foregoing temperatures.

(3) Argon, helium and nitrogen at 160° C, all at one atmosphere.

The measurements were made by the method of "multiple observations" wherein two complete sets of data were taken at each of several levels of power input to the cell heater. The results showed a somewhat astonishing and not fully understood phenomenon. It proved impossible to adjust the heat station or the furnace heaters to bring all the indications of all four thermocouples on the emitter to the same temperature. Three could be made the same, with the remaining one several microvolts higher, and similar related conditions. The magnitude of these effects increased with power input and also with the presence of gas in the cell. The effect was quite small however in vacuum, and fairly large with air, argon and nitrogen. The question of whether the effect is the result of a real temperature difference or of electrical origin cannot be answered with certainty although some indications point to a real temperature difference.

For air, argon and nitrogen, the results from experiments with different temperature distributions varied over a range of about ten per cent. However the experiments with helium, requiring much greater power input to the emitter, but having a deviation from temperature uniformity of the same order of magnitude as found when using air, gave results which

differed very little with different temperature distributions. This is indeed what would be expected if the temperature differences were real and the different results for air, argon and nitrogen were the result of varying contributions of the end losses to the consumption of the input power.

It would seem that the design of the cell is not yet that which would allow good precision in the measurement of heat conductivity at high temperatures. An arrangement that may eliminate the present difficulties described would be the employment of a more massive emitter (say 4 mm O.D., 2 mm I.D.) in which the central section is sharply differentiated from the heat station sections by isolating segments of the emitter having relatively high resistance to axial flow of heat.

PRANDTL NUMBER DETERMINATION BY MEANS OF RECOVERY FACTOR MEASUREMENTS

University of California - Phase 1

R. A. Seban, Phase Leader
S. Scesa

Introduction

It has been demonstrated analytically that the recovery factor for a gas flow over a surface upon which the free stream velocity is constant is a function only of the Prandtl Number of the gas. This is true for the case of constant properties and it has also been shown analytically that small property variations cause but a negligible change in the relation that obtains for the constant property case. Accurate measurements of the recovery factor then can be used to infer the Prandtl Number of the gas through the relation:

$$r = 1 - \frac{T_s - T_0}{T_s - T_1} = \sqrt{\frac{\mu c_p}{k}}$$

T_s is gas stagnation temperature, T_1 the free stream temperature,

and T_0 the temperature of the adiabatic wall over which the gas flows.

The experimental system must provide a nearly adiabatic wall, and a surface over which the velocity of the gas is practically constant. The first criterion is the one most difficult to realize and is approximated by attaining on the test surface a high convective heat transfer coefficient and a low emissivity for thermal radiation. With the arrangement as devised, this is realized well enough to allow the Prandtl Number to be inferred with an error of less than 1 per cent at a temperature of 700° F.

The experimental system is a closed gas circulation system, containing a blower, nozzle, and cooler, arranged to provide, particularly in the nozzle section, a region of uniform temperature equal to the gas stagnation temperature. Adiabatic wall temperature measurements are made on the surface of a $\frac{1}{4}$ inch diameter probe mounted axially in the nozzle. The probe, made of platinum, .006 inches thick, has an ogival nose and contains, in addition to the thermocouple, a static pressure tap, from which indication the free stream state temperature, T_1, is inferred.

Discussion

In the previous status report the preliminary operation of this system was indicated, and some results were given for air at relatively

low temperatures. Since that time, data have been obtained for air for temperatures between 125° F and 625° F, from which the following magnetudes of the Prandtl Number are typical.

Temperature °F	125	200	300	400	500	600
Prandtl Number	.694	.687	.679	.674	.673	.672

These values agree within 1 per cent with values reported by Keyes(1) and are the NBS-NACA(2) tables. Similar agreement is attained with values of the Prandtl Number calculated from individual properties when the values of Glassman and Bonilla(3) are used for the thermal conductivity.

Further operation of the system was intended on different gases and mixtures of gases, and this program has been retarded by necessary repairs to the equipment as constructed to attain the tightness necessary to such operation. This involved re-welding and re-gasketing of parts of the apparatus and the construction of a new blower case, and this work has required much of the period covered by this report.

Notes and References

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MEASUREMENT OF CONVECTION AND RADIANT HEAT TRANSFER COEFFICIENTS FOR HOT GASES

Purdue University - Phase 5

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B. A. Reese, Assistant Project Director
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Jacobus M. Botje
Wayne J. Colahan

Introduction

This investigation is concerned with obtaining data on the contributions of radiation and convection to the total heat transferred from a hot flowing gas to the cold wall of a metal tube, as well as determining the effect of pressure upon radiant heat transfer. It is planned to obtain these data at pressures up to 500 psia, temperatures up to 2500 R, and over a Reynolds number range of 10,000 to 50,000.

The radiant heat transfer coefficients will be obtained in the following manner. From experiments with a non-radiating medium at the above-mentioned conditions, the convective heat transfer coefficients will be obtained.

Similar experiments under the same conditions with a radiating gas will yield coefficients which are a combination of those due to convection and radiation. At the same Reynolds number and temperature, the difference between the total heat transfer coefficient and the convective coefficient will yield the heat transfer coefficient due to radiation alone. The data obtained will materially aid in eliminating many of the assumptions currently required in predicting the heat transfer in rocket motors.

Discussion

(a) Flow Measurements. The calibration of the entire flow measuring system has been completed. The flow measuring system which employs both small diameter sharp edged orifices and small diameter sonic orifices has been previously described (1, 2). The system has been modified by incorporating sonic orifices instead of sonic nozzles because the sonic orifices give discharge coefficients that are more reproducible and consistent.

The sonic orifices were calibrated using air both at ambient temperatures and moderately high temperatures (up to 850 F) over a range of upstream pressures from 50 psia to 450 psia. The flow coefficients were reproducible within 0.5 per cent in all trials. The maximum deviation of the flow measurements made with the sonic orifices based on comparative measurements with the sharp edged calibrated orifices operating in the incompressible flow regime was 1.0 per cent. When the sonic orifices were calibrated at elevated

temperatures the area of the sonic orifices was corrected using the area multiplier specified by the ASME Code for A.I.S.I. type 304 stainless steel (3).

(b) Pure Convective Heat Transfer. The entire flow system was assembled and pressure tested. The flow system is comprised of the following elements:

(a) Sharp edged orifice assembly;

(b) Inlet mixing chamber;

(c) Gas fired furnace and heater coil;

(d) Water cooled heat transfer section;

(e) Exit mixing chamber; and

(f) Stagnation chamber and sonic orifice.

Guard heaters were installed around the inlet section from the furnace coil outlet to the discharge end of the inlet mixing chamber. A guard heater was also installed around the exit mixing chamber. The guard heaters around the inlet section serve a dual purpose; they reduce the time for bringing the system to the required temperature, and provide a means for accurately controlling the temperature of the gas entering the inlet mixing chamber. The guard heater surrounding the exit mixing chamber serves only the former purpose and is shut off once the system has reached the test temperature.

Before convective heat transfer experiments with the non-radiating gas were initiated, a series of preliminary experiments were conducted with heated air for establishing the best procedures for starting and shutting

down the system and the emergency shut-down techniques.

The first series of heat transfer experiments were conducted initially with air and then with nitrogen. Runs were made at 1500R, 1700R, and 1900R (temperatures indicated are those of the gas in the inlet mixing chamber unless otherwise specified). The values of the heat transfer coefficients obtained for the two gases under similar conditions were practically identical. Consequently, in the interest of economy, the use of nitrogen was discontinued and dry air was employed as the convection medium in all subsequent experiments. Because of insufficient high pressure air storage capacity it was not possible to conduct experiments at pressures above 250 psia. It is planned to increase the high pressure air storage capacity so that experiments can be conducted at pressures up to 500 psia.

Convective heat transfer data for dry air were obtained under the following conditions: temperatures of 1500, 1700, 1900, 2100, 2300, and 2500R, and pressures of 50, 75, 100, 125, 150, 200, and 250 psia. At each of the aforementioned temperatures, data were obtained at each of the above-mentioned pressures with the exception of the runs at 2500R. At 150 psia and 2500R the flange section of the inlet mixing chamber failed by rupture; the flange was made of mild steel because stainless steel was unavailable at that time and hence the flange was not expected to withstand the extreme conditions of temperature and pressure. A new section has been built of stainless steel and is currently being employed for tests. The data obtained up to this time cover a Reynolds number range of 11,000 to 100,000. More

data will be taken in the lower Reynolds number range of 10,000 to 20,000.

Calculations of the convective heat transfer coefficients for air as a function of the Reynolds number, utilizing the data obtained thus far have been completed. The physical properties of the gas were evaluated at the average bulk temperature, and the data were correlated by the method suggested by Colburn (4). Colburn's relation is as follows:

$$j = St\ Pr^{2/3} = 0.023\ Re^{-0.2} \qquad \text{(a)}$$

where

St = Stanton number $\frac{h}{C_p G}$

Pr = Prandtl number

j = Colburn factor.

Figure 1 compares the experimental and theoretical values of the Colburn j factor as a function of the Reynolds number. Although the deviation of the experimental data from the straight line suggested by equation (a) at any one point is small, the experimental results indicate that they are more closely correlated by a line with a slightly different slope. This is denoted by the dotted line in Figure 1. More data are necessary, however, in the lower Reynolds number range to establish this trend more definitely. The data were reproducible because points at the same Reynolds number to within $\pm$ 5 per cent. Reproducibility is important because it determines the usefulness of the current method of investigation for evaluating the heat transfer coefficients from a radiating gas.

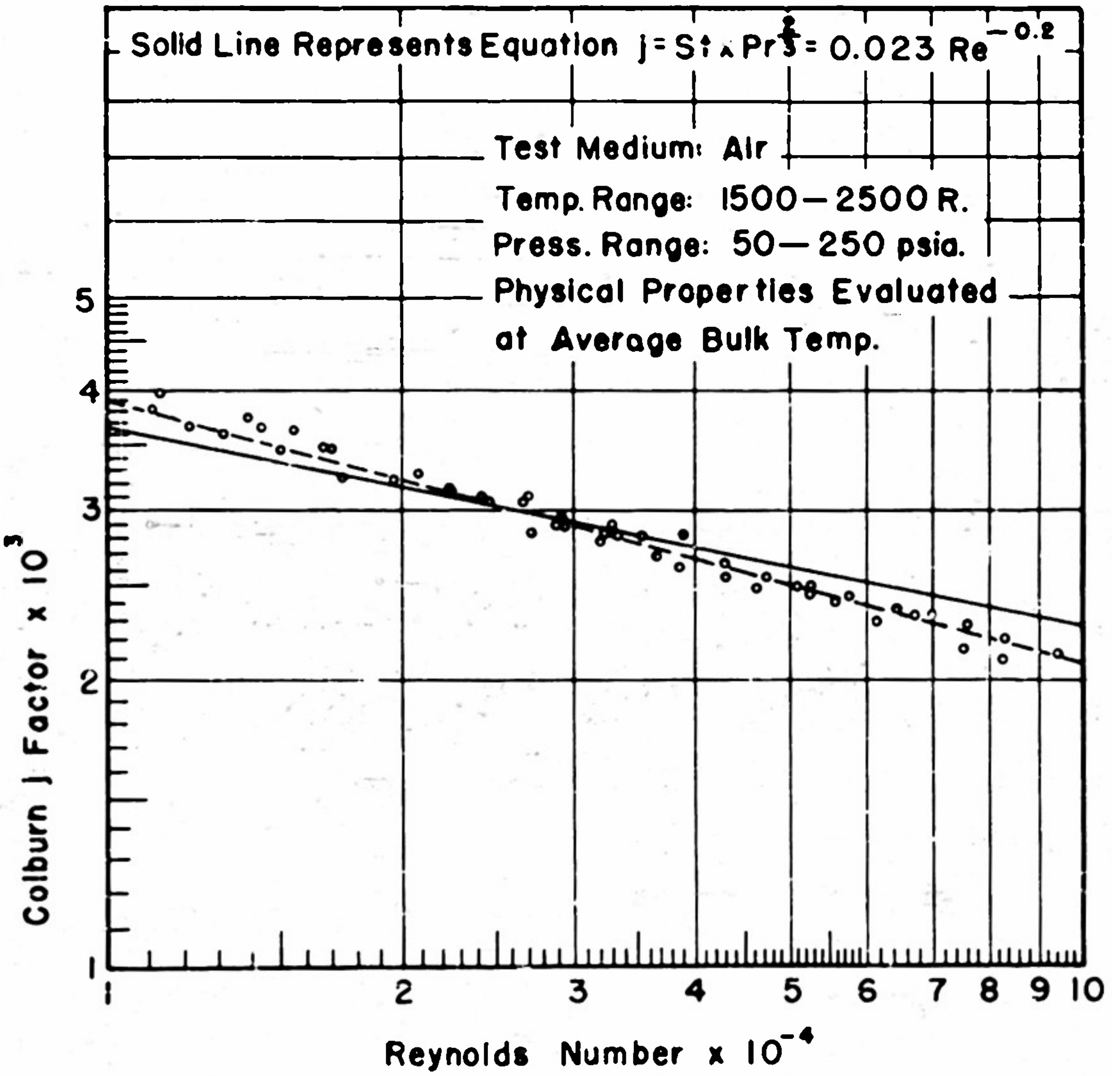

Fig. I. Correlation of Heat Transfer Data.

The data obtained to date extend the range of published data. Most of the published data were obtained at temperatures less than 1000R. Data obtained at higher temperatures were obtained at pressures of two atmospheres or less.

The accuracy of the data reported herein can best be established by a heat balance of the test system and its reproducibility of the heat balance. In all cases the average heat balance uncorrected for radiation losses was ± 3.5 per cent, i. e. the maximum average difference between measured heat transfer to the flowing gas and that transferred to the cooling water was 7%.

It is estimated that the final data using the non-radiating gas will be obtained within the next few weeks and test runs using the radiating gas will begin immediately thereafter.

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INVESTIGATION OF COOLANT FILM STABILITY IN THE TWO- AND THREE-DIMENTIONAL CASES

Purdue University - Phase 10

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Arthur B. Greenberg, Phase Leader
Robert K. Louden

Introduction

This problem is concerned with the experimental investigation of the stability of liquid films formed by injecting a liquid through spaced parallel disks into an air stream. The object of the study is to obtain data which will establish the conditions for producing a stable liquid coolant film, for cooling purposes, on the walls of a tube through which a hot gas is flowing. The criterion of film stability adopted for this investigation is the magnitude of the critical velocity of injection, defined as the maximum mean velocity of the injected liquid that does not produce separation of the liquid film from the test section wall. Accordingly, a systematic investigation of the critical velocity of injection as a function of air velocity, slot con-

figuration, liquid properties, and gas stream properties has been undertaken, and the experimental results obtained for a number of the aforementioned parameters have been reported (1, 2, 3, 4, 5, 6).

Discussion

The experimental program of this phase was suspended for approximately four of the six months of this report period as a result of a fire which occurred in the laboratory on 20 March 1953. The fire completely destroyed the air system employed in the experimental investigations. Consequently, much activity was directed toward the reconstruction of the laboratory, and only recently have experiments been resumed.

Owing to the short time available for testing during this report period only limited data on film stability have been obtained. Experiments are now in progress to determine the effect of the inside diameter of the air duct on the critical velocity of injection. The experiments are being conducted with a slot configuration which provides radial injection of the liquid (water) into a constant-area circular air duct. The experimental parameters being studied in the latter investigation are:

a. tube inside diameters of 1 1/4 inch, 1 1/2 inch, 2 inch, 2 1/2 inch, and 3 inch;

b. mean air velocities of 100 fps to 500 fps; and

c. slot widths of 0.005 inch, 0.010 inch, 0.015 inch, and 0.025 inch. At the time of this writing the aforementioned experiments are 60 per cent complete. The partial data indicate a significant increase in the critical velocity of injection as the air tube diameter is decreased.

During the aforementioned delay in the experimental program designs were begun for the high-pressure air system. The latter system is to supply large flow rates of air for the study of film stability and film cooling at elevated pressures (35 psig to 400 psig) and elevated temperatures (100°F to 2000°F). The system, as designed, will include fourteen Mark 15 torpedo flasks, a 3000 psi air compressor driven by a 75 hp diesel engine, an automatic pressure-reducing valve system, a propane-fired combustion chamber, an automatic temperature control system, a test section, and the necessary associated piping and safety features. The piping system has been designed and construction will be started in the near future.

Notes and References

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POROUS COOLING STUDIES

Polytechnic Institute of Brooklyn - Phase 3

S. W. Yuan and P. A. Libby, Phase Leaders

Introduction

These studies are concerned with the experimental determination and theoretical investigation of the laminar and turbulent boundary layer characteristics on a porous surface with zero axial pressure gradient and with uniform mass injection. The skin friction, heat transfer and transition characteristics of such boundary layers are being investigated. In addition, the case with axial pressure gradient is being pursued with particular reference to the sweat cooling of turbine blades.

Discussion

Experimental Studies on Flat Plates: During the past six months the

isothermal investigation of the turbulent boundary layer on a flat plate with uniform injection has continued. Difficulties in determining a satisfactory length correction to bring the experimental results in agreement with the ideal turbulent boundary layer on an impermeable flat plate have been encountered. It is still not clear whether these difficulties are due to inlet conditions, to the narrowness of the channel in which the measurements are being made; or due to the axial pressure gradient. Each of these possibilities is being investigated.

In order to reduce the amount of experimental work required and to permit comparison of the experimental results with the measurements of Mickley,[1] et al, his data have been analyzed from a point of view, differing from his own. It is well known that in analyzing turbulent boundary layer measurements a length correction to account for the initial conditions of the boundary layer must be made to the geometric length. This correction is usually based on theoretical considerations or on previous measurements. It is usually the aim of the boundary layer experimental technique to make the length correction small and thereby to permit relatively large inaccuracies in its determination without affecting the overall results.

The data presented by Mickley has been analyzed from this point of view. It has been found that with injection, a length correction is extremely important and its consideration leads to an entirely different interpretation of the data. This sensitivity to a length correction

could be expected from a consideration of the small differences involved in computing the skin friction from the momentum theorem.

One reasonable analysis proceeds as follows: It is hypothesized that with injection the average and local skin friction vary with the same power of the local Reynolds number R_x as in the impermeable wall case, and that the multiplier of R_x would be a function of the injection ratio v_o/U; thus if the Blasius friction law is used,

$$C_f = A\ R_x^{-1/5}$$

where $A = A(v_o/U)$. With this assumption taken as a working hypothesis, it is possible to interpret Mickley's data and to find that this hypothesis is in good agreement with the experimental data. The values of A obtained from this analysis are as follows:

v_o/U	A
0	0.076
0.0021	0.060
0.0050	0.035
0.0099	0.0076

Mickley's data covers a range of Reynolds number up to one million. Whether this hypothesis holds for higher Reynolds number is not known at this time.

It is the intention to obtain additional experimental data to check the hypothesis mentioned here.

The construction of the high temperature channel has continued.

The support for the channel has been constructed and the channel mounted. The cooling system is being designed and thermocouples installed in the porous plate. Initial operation of the tunnel should take place within the next six months.

Sweat-Cooling of Turbine Blades: The investigation of the efficacy of localizing the sweat-cooled region on a portion of the surface upstream of the exposed surface has been completed. A report on this work is being prepared. In this final analysis the influence of the upstream injection on the velocity and stagnation enthalpy profiles as well as on the boundary layer thickness has been considered. At the discontinuity where the injection ceases and the wall is assumed to be thermally insulated, the mass, momentum and energy within the boundary layer have been made continuous by the inclusion of additional parameters in the velocity and stagnation enthalpy profiles. These parameters are constant downstream of the discontinuity and take on those values required to make the mass, momentum and energy continuous across the discontinuity. The insulating ability of the laminar boundary layer as predicted by this more exact analysis, is quite good. Its application to airfoils at a Mach number of 4 and at 40,000 ft. altitude and to cooling hypersonic wind tunnel walls has been considered. It is found that only small rates of fluid injection are required.

Theoretical Study of the Turbulent Boundary Layer: A theoretical investigation of the friction coefficient for the pipe flow with injection has been made. In the case of the laminar flow the von Kármán

momentum equation in cylindrical coordinates has been solved. From the continuity equation the rate of change of the maximum velocity in the pipe with the length of the pipe in the flow direction and with the quantity of injection can be established. The solution of the above equations gives the maximum velocity and the pressure gradient in the pipe as functions of the quantity of injection, the Reynold's number and the dimension of the pipe. The friction coefficient can then be determined from the pressure gradient and the velocity gradient in the flow direction as a function of the quantity of injection for the given pipe. The results indicate that friction coefficient increases with the increase of injection.

The same type of results have been obtained in the case of turbulent flow in a pipe. However, the pressure gradient and the velocity gradient in the pipe were obtained from the experimental data of the Jet Propulsion Laboratory of California Institute of Technology.

The physical interpretation of the above results can be made from the following reasonings. In the flow over a flat plate with injection the maximum velocity in the potential fl w is constant and the pressure gradient in the flow direction is zero. The fluid injection would increase the thickness of the boundary layer, hence the shearing stress at the wall decreases with the increase in injection. In a fully developed pipe flow, the quantity of flow injected into the pipe would accelerate the flow; thus the velocity gradient in the flow direction

is increased and the pressure gradient is decreased. Hence, the wall shearing stress increases with an increase in injection.

The above results will be used in the investigation of transpiration cooling of a porous pipe for which some experimental data exists.

Notes and References

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VAPORIZATION AND COMBUSTION OF MULTI-COMPONENT FUEL DROPLETS

Northwestern Technological Institute - Phase I

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Introduction

This study is concerned with the vaporization and combustion processes occurring with multi-component fuel sprays under conditions approaching those in the combustor of a turbo-jet engine. Information with respect to the effect of evaporation from droplets on the composition of residual liquid, as well as on the rates at which such vaporization occurs, is sought. Interpretation of such observations to allow generalizations of analytical significance is the ultimate objective.

Discussion

Work has been continued on the experimental determination of the vaporization characteristics of several two-component liquids in spray droplet form injected downward through various heights of quiescent air at various temperatures. The duration of runs at given conditions were varied, and the results were extrapolated back to zero feed volume to evaluate the evaporation and change in droplet composition applicable to the first group of droplets entering the air chamber. This avoids the necessity of considering the variation in partial pressures of the vaporized liquids in various portions of the air chamber as the spray injection proceeds. The data show that the higher boiling component concentrates in the residual droplets as the evaporation proceeds. In the range of air chamber temperatures from 400°F to 1000°F and from 10% to 60% evaporation of the sprayed liquid, the concentration of the higher boiling component proceeds more rapidly at the higher air temperatures. This indicates that diffusion or convection of mass within the droplets (from 10 to 200 microns in diameter) increases more rapidly than the increased rate of evaporation due to the larger temperature difference between the air temperature and the droplet surface. This is the opposite of the effect predicted by Topps (1), who postulated that, as the rate of heat transfer to a droplet increased, the diffusion within a droplet would become relatively negligible; and, therefore, the residual droplet composition would be the same as that of the

original droplets.

It is of interest that the moving pictures of Professor P. S. Myers shown at the Conference on Atomization (2) showed a high degree of circulatory motion within a suspended droplet, which would be consistent with our observations on changes in composition. The high mass transfer coefficients reported by Professor H. F. Johnstone at this conference also confirm rapid diffusion or convection within droplets formed in a Venturi atomizer. The droplets used by Myers were about 2000 microns in diameter, but our data on mass transfer within spray droplets of about 100 microns in diameter at relatively high velocities, within say 15 inches of a nozzle, appear to indicate that considerable convection occurs inside the drops. This is apparently due to the viscous drag forces between the air and the droplet. This appears to be true even though the surface tension forces on the droplet may be sufficient to cause it to form a spherical droplet with no noticeable oscillations between oblate and prolate ellipsoids of the type reported with larger single droplets.

Attempts to run our apparatus with higher air temperatures (above 1000°F) resulted in fires even though we were using halogenated hydrocarbons, such as ortho-di-chloro-benzene to reduce inflammability hazards. The use of an inert nitrogen atmosphere instead of air was tried and reduced the fire hazard, but resulted in slow work and excessive nitrogen requirements. Therefore, while work was continued on the large apparatus on other two-component liquids at temperatures below the inflammability

limits, a smaller apparatus was built with a one-cubic-foot spray chamber and a preheater for heating the nitrogen for the system. Some difficulty with burning out of heater coils is being encountered currently; but it is anticipated that test data at higher inert gas temperatures can be obtained to see if the higher rates of heat transfer to the droplets will reverse the trend of our data.

As has been indicated in previous reports, supplementary work at higher pressures and temperatures has been planned using a two-inch, steady flow, spray nozzle type, combustor unit.

Completion of equipment for air supply and measurement, liquid fuel metering and injection (i.e. - the combustor), temperature and pressure measurements and quenching and venting of hot combustion product gases has been accomplished. This places this unit in a condition ready for combustion. Initial experimentation, however, requires the use of a preburner or gas preheater now under construction to provide high temperature inert gas to allow vaporization of liquid fuels without the immediate presence of flame. Development of a satisfactory means of sampling residual liquid droplets is being pursued. It is expected that, in those studies with flame absent, "fuels" comprised of two-component liquids will be injected into the preheated air stream at the "combustor." The apparatus is designed also to inject and actually burn combustible fuel for future studies of evaporation with flame present and of the kinetics of combustion.

Notes and References

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COMBUSTION STUDIES WITH PRE-MIXED PARTLY VAPORIZED FUELS

Dartmouth College - Phase 1

J. A. Browning, Phase Leader

Introduction

The relative importance of small liquid droplets on such combustion phenomena as flame velocity, flame stability, and the lean and rich limits of combustion is being studied. A fog of an inflammable liquid is injected into a combustible gaseous mixture and the effects noted. Droplet size is determined by use of optical diffraction equipment capable of measuring particles with diameters as large as 30 microns.

Discussion

Any system which introduces liquid fuel as a spray, or fog, into air is necessarily complicated by the presence of both the liquid and vaporized

forms of the fuel. It is believed that a homogeneous mixture of fuel vapor and air would represent optimum conditions for combustion. Higher injection pressures with a greater degree of atomization of the fuel is used to attain the maximum possible vaporization rates. The heat required to vaporize this fuel is obtained from the surrounding medium. It may be possible to increase heat transfer rates to the point where flame propagation suffers. The effect of a combustible liquid fuel fog on Bunsen flame velocity, flame stability, and the lean and rich limits of combustion is being studied. The fog produced from a liquid fuel is introduced into a combustible mixture of propane and air. It is believed that such a fog is nearly monodisperse and thus its droplet size and concentration may be measured by optical diffraction methods.

The lean and rich limits of combustion will be measured by a "bomb" technique. A constant volume bomb has been constructed from a small oxygen cylinder. A device consisting of a Crosby engine indicator with a rapidly rotated drum has been adapted for measurement of combustion pressures. Means for admitting accurately metered quantities of air, propane, and liquid fuel fog are incorporated in the design. Ignition is by spark discharge. The combustion limits for a mixture of propane and air alone will first be determined and then compared with that of a mixture containing the fog.

The optical apparatus closely follows a design developed by the Department of Chemical and Metallurgical Engineering at the University of

Michigan (see References 1, 2, and 3). Heretofore only particles with diameters less than about 1 micron have been successfully measured by diffraction methods. As the particle diameter is increased beyond the wavelength of the incident light, a greater proportion of the light is scattered within a small solid angle in the forward direction. Thus, for these larger sizes light-transmission measurements without geometric information concerning the forward scattering angle are meaningless. Light scattering functions adaptable to larger particle sizes have been compiled by the University of Michigan.

A two-watt concentrated Zirconium arc is the light source. A 16 mm, f/1.6 projection lens produces a parallel beam of light of approximately 1 mm diameter. This beam passes through the mixture containing the droplet suspension. A lens-pinhole system prevents the scattered light from reaching the photo-multiplier tube (RCA 1P21) and only that portion of the beam contained within a known forward angle may be measured.

The transmitted light I is the incident light I_0 less the amount scattered at an angle greater than θ (the solid angle in the forward direction through which the light may reach the phototube). Following is the basic transmission equation adapted for known values of θ:

$$\frac{I}{I_0} = e^{-RK_t \frac{\pi D^2}{4} ni}.$$

K_t is the total scattering coefficient and may be defined as the ratio

between the total scattering cross-section and the geometric cross-section of a particle of diameter D. The droplet concentration n represents the number of particles per unit volume, while l is the length of path of the light beam through the suspended medium. R is a "correction factor" which takes account of the forward angle θ. Two unknown quantities are contained in the equation — the droplet diameter and concentration. As both R and K_t are functions of the wavelength of the incident light, simultaneous equations may be obtained and solved by use of different wratten filters (see Reference 4).

References

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INVESTIGATION OF THE BASIC PROBLEMS ASSOCIATED WITH GASEOUS COMBUSTION

University of Delaware - Phase 2

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Introduction

This study is concerned with the combustion characteristics of laminar and turbulent flames. This field has been divided into four interrelated problems: 1) A spectrophotometric investigation of flame radiation from the ultraviolet to the near infrared. The goal is to follow the rise of temperature and concentration of combustion products, and the rise and decay of radical radiation, through a flame front in order to contribute to our knowledge of flame front structure and combustion kinetics. 2) A study of open turbulent flames burning above tubes and sta-

bilized by a pilot flame ring at the rim. The purpose of this work is an analysis of the concepts of burning velocity and depth of flame. The experimental method consists in a densitometric evaluation of flame photographs, chemical analysis and instantaneous and high speed motion schlieren photography. 3) A study of turbulent flames burning in ducts and held by simply shaped blunt objects. This work has partly similar aims as that mentioned under 2). It is hoped that a comparison of open and enclosed flames will throw light on the causes of what is called flame-created turbulence. 4) Measurement of time averages of temperature and temperature fluctuations. The sodium line-reversal method is used as a tool in the different problems of this phase. Besides, a method has been developed for measuring temperature fluctuations of luminous flames and has been applied at present to turbulent diffusion flames.

Discussion

Problem 2R1 - Turbulent Flames Burning Above Tubes. Work has been continued on the study of turbulent Bunsen flames by densitometric evaluation of flame photographs. Average turbulent burning velocities have been determined from the surface of maximum luminosity for butane-air flames burning from tubes of different diameter (0.4 inch, 1.0 inch, and 1.5 inches). The ex-

periments confirmed basically the observation of Williams and Bollinger (1) that the turbulent burning velocity increases with increasing tube diameter d. At equal flow velocities through the burner tubes, the turbulent burning velocity S_t was found to be proportional to $d^{0.4}$. At equal Reynolds numbers proportionality with $d^{0.1}$ was observed. It is suggested that this is due to an increase of flame length with increasing tube diameter since, according to Karlovitz et al. (2) and Scurlock (3), the local turbulent burning velocity increases with increasing distance from the flame base, at least as long as there is an essentially continuous instantaneous flame surface (see also the following section and Wohl et al. (4)).

It was mentioned in the previous Semi-Annual Progress Report that the turbulent burning velocity of butane air flames, at otherwise equal conditions, increases with increasing fuel concentration. Since a slight effect of the surrounding air on the measured burning velocity cannot be excluded with safety experiments have been started in which the flame burns in an environment of nitrogen. At these conditions the intensely luminous main reaction zone is surrounded by a very extended and quite luminous diffuse aureole. An automatically travelling and recording densitometer has been constructed which is being used to measure the luminosity profiles of the flames at various heights. From these profiles the true luminosity of a

flame element along a traverse perpendicular to the flame axis is being determined by a stepwise procedure. These data will be used to give values for the thickness of the burning zone and improved values for burning velocity.

Problem 2R2 - Turbulent Flames Burning in Ducts. In the previous Semi-Annual Progress Report a brief account was given of experiments with propane-air flames which were burning in a duct of a cross-section of 1.5 inches x 2 inches and a length of 10 inches. The 2-inch walls consisted of quartz. The flame holder was a plate which was placed between the two center lines of the quartz walls and was 1/4 inch thick.

The study of the structure and behavior of such flames with the help of high-speed schlieren motion pictures (6400 frames per sec.) has been greatly extended. The flame fronts of "normal" turbulent flames, i.e. of those which do not show the "waves" described in the previous report consist of curved elements which are relatively stable except for growing while travelling downstream, and which are separated by incisions which in some case nearly reach the flame axis. The scale of this structure is smaller with rich flames than with lean ones. A sufficient degree of approach stream turbulence ($\sim$ 9% produced by a 4 mesh grid) destroys any regular flame structure, produces fluctuations of very small scale and very large intensity in the

flame and promotes spreading to such a degree that the duct is for the most part uniformly filled with a coarse mixture of gas elements in which combustion has progressed to various degrees. If rich, these flames show violent irregularities.

The "waves" which were previously observed at high velocity and low approach stream turbulence do not appear if the gas mixture is very lean or very rich, and if the approach stream turbulence is very high ($\sim$ 9%). In the first two cases there is not enough energy, in the last case there is too much disturbance, for creating the oscillations of the residual flame at the flame holder which are responsible for the appearance of the waves. A change in flame holder configuration did not eliminate the waves. This was proved for flame holders of the shape of a cylinder, a thin strip and a long plate with its downstream end rounded off.

Blow-off, on the lean as well as on the rich side is preceded by a smoothening of the flame zone structure and by spotty burning. As a result of the latter, the whole interior of the flame - which normally remains invisible in the schlieren picture though the turbulence may be high - fills with a well visible mixture of hot and cool gas elements, which do not show any strong macromotion (circulation).

In the experiments described in the preceding Semi-Annual Progress Report only 30% (not 13% as was stated erroneously) of the combustible gas mixture burned within the 10 inch duct. In order to be able to study combustion in more advanced stages a new chamber was fabricated which has the same cross-section as the previous one but is 20 inches long. The difficulty in using this chamber consists in the fact that the flames immediately upon ignition flash back due to the increased back pressure of the burned gases. This difficulty can be overcome by providing for a gap in one of the chamber walls halfway down the chamber which is open during ignition and is subsequently closed. The range in which flames can be studied without the disturbing factor of wave formation has widened; but the stability range is somewhat reduced.

The hot-wire anemometer which had been built and used in this department for intensity and scale measurements in the approach stream was inoperative for a considerable time because of irregular operation. A direct-coupled amplifier (type 112, Tektronix, Inc.) has now been obtained as the "heart" of a feedback, constant-resistance hot-wire anemometer system. The hot-wire is one element of a Wheatstone bridge circuit which forms the load resistance of a cathode follower circuit. The latter is driven by the output of the Tektronix amplifier and is able to furnish the wire heating current by using several tubes in

parallel. The system has been found to operate very satisfactorily and with good stability. The fluctuating voltage is amplified by an AC amplifier and measured with a sensitive thermo-milliammeter. A second such system has been put into operation for the purpose of measuring the scale of turbulence.

Problem 2R3 - Measurement of Flame Temperature Fluctuations. A study has been made of the fluctuations of visible radiation (emitted by carbon particles), temperature and absorptivity of turbulent diffusion flames. Fluctuations are responsible for the turbulent mixing process which determines the progress of combustion in such flames. But no direct measurements of the fluctuations of any quantity in these flames has so far been made. The closest approach to it is the determination of the unmixedness factor by Hottel et al. (5). Hottel as well as Baron (6) assumed a Gaussian error distribution of fluctuations. But periodic processes and distortions of the distribution curve through other factors cannot be excluded so that an experimental investigation of distribution curves has here been undertaken. Besides, the average values of the quantities mentioned, the absolute and relative values of their mean deviations from the average, the mean frequencies of fluctuations, and the frequency spectrum, have been measured at various flame conditions and places in the flame; also the question of coupling between the fluctuations of temperature and absorptivity has received attention.

The average radiation intensity and the mean of its fluctuation have been measured directly with the help of a phototube. The average temperature and absorptivity have been determined by comparison with a standard lamp. The fluctuations of the two latter quantities have been obtained from photographic records of oscilloscope traces which had been produced by alternating 5000 times per second between radiation from the flame and from the lamp shining through the flame. The optical pencil used for probing the flame had a diameter of 1/4 inch. Flames have been studied which were produced by freely burning cylindrical fuel jets and by fuel streams emerging from a slot between two walls (two-dimensional diffusion flames). The fuel was mostly acetylene and occasionally pure and air-diluted butane. Horizontal traverses through the two-dimensional flame were of special value since in this case the average flame properties along the optical path were uniform so that profiles of these properties could be obtained directly. The fluctuations recorded represented in any case the resultant of all the fluctuations along the optical path. The evaluation of data is still in progress.

At low and medium heights, the profiles across two-dimensional acetylene diffusion flames show minima of average temperature, light intensity and absorptivity in the axis, and maxima on either side at distances from the axis which are largest for

temperature and smallest for absorptivity. At larger heights the profiles are smoothed out, absorptivity in the interior rising with increasing flame height to 100%. The temperature values at the maximum decrease with increasing flame height and decreasing velocity. These observations can be explained by an interplay of turbulent transport of material and heat, cracking of fuel and gradual accumulation of soot in regions of moderate temperature and low content of air,and rapid consumption of soot in regions of high temperature and air-fuel mixtures of about stoichiometric proportions. The mean fluctuations of radiation intensity follow roughly those of the average intensity. The relative fluctuations which may serve to define flame turbulence in a special manner are around 30%, with much higher values in the outer sections of the flame front where the absorptivity(soot concentration)is very low.

If the two-dimensional flame is viewed through the two burning zones the average radiation intensity and temperature pass through a maximum with increasing height while the absorptivity continuously increases. The absolute and relative mean fluctuation of radiation also pass through a maximum, and it is noteworthy that the latter becomes independent of velocity beyond the maximum which is quite close to the port.

Data obtained with acetylene flames produced by jets which

emerged from openings of different type and diameter at different velocities, showed many similarities with the last mentioned data. On the whole, average intensity, temperature and intensity fluctuations pass through maxima with increasing height. The absorptivity rises continuously with height for the larger jet and passes through a maximum for the smaller jet, obviously because in the latter case the soot in the interior of the flame starts to be consumed by burning. All axial data for cylindrical and two-dimensional flames correlate moderately well if compared on the base of the ratio of height to total observed flame height.

The radiation intensity fluctuations of acetylene and butane jets have also been studied with the help of a wave analyser. The power spectrum can be well represented by the theoretical equation $E_n / E_o = 1/(1+n/n_{1/2})$ where E_n is the radiation energy per frequency range 1 at the frequency n. E_o and $n_{1/2}$ are constants. The term $n_{1/2}$ characterizes the frequency range. For acetylene jets the value of $n_{1/2}$ was found to increase with velocity and decrease with height. In an acetylene flame burning from a 0.033 inch tube the characteristic frequency varies between the following extremes:

Velocity 97 ft./sec., height 6 inches, $n_{1/2} = 250$

Velocity 275 ft./sec., height 2 inches, $n_{1/2} = 1700$

The frequencies in butane flames are of the same order of

magnitude.

The fluctuations of temperature and absorptivity in acetylene and butane jet flames were studied by an analysis of the photographs of oscilloscope traces mentioned above. It was first ascertained that the probability curve for temperature did not deviate much from the Gaussian error curve though in a number of cases a more abrupt drop of the experimental curves towards low temperatures was noticed. The half-spread of temperature for acetylene flames was around 160°C. The highest single temperature measured for acetylene and butane flames was a little more than 100° below the maximum adiabatic combustion temperature. The lowest single temperature for acetylene was 1390°K, that for butane 1650°K. For comparable conditions, however, the lowest temperature in an acetylene flame was only slightly below that in a butane flame.

With the smaller acetylene jet the measurements were continued nearly to the visible flame tip. At this height the flame flickered so that there was a finite probability for the absorptivity zero. With the larger jet, on the other hand, the average soot concentration at large heights corresponded to an absorptivity of about 1 . In either case the distribution of absorptivity deviated strongly from a Gaussian error curve. The absorptivity of butane flames was much smaller than that of

acetylene flames and the distribution followed more closely the Gaussian error curve.

The fluctuations of temperature and absorptivity were coupled in such a way that there was a likelihood for the temperature to be high if the instantaneous absorptivity was low and vice versa. This shows that the fluctuations consist in rapid changes of the rate of burning, inclusive burning of the amount of carbon. In case of acetylene flames the mean temperature associated with a given instantaneous value of absorptivity depends on flame conditions while for butane flame a common curve covering several conditions is obtained. This seems to show that in acetylene flames the soot concentration is the result of a slow accumulative process while in butane flame the carbon production, just as its consumption, is a rapid process which is mainly determined by the instantaneous local situation.

A rough estimation of the frequency distribution of temperature and absorptivity, besides radiation intensity, has been obtained from the photographic recordings of fluctuations by counting the different periods between the minima and maxima of the traces regardless of amplitude (though above a certain minimum amplitude). From this procedure it was learned that nearly the same frequency distribution was obtained for all the three quantities - which is another proof of the extremely rapid mutual

adjustment of soot concentration and temperature.

Problem 2R4 - Flame Radiation Studies. A method for measuring the temperature of flames from the intensity ratio of the radiation at two peaks of the infrared water bands (any combination of the peaks at 2.505, 1.819, and 1.346 μ) has been developed in this department (7). The method presupposes that the radiation is thermal, i.e. that absorptivity equals emissivity. This has been verified now at 2.505 μ for several slit widths, and it has been ascertained that the emissivity is independent of slit width over a considerable range above 0.11 mm, the normally used width being 0.13 mm corresponding to 200 Å resolution. (The two other wave lengths will be tested in the near future). Proportionality of emissivity with water vapor concentration at a fixed temperature was established now for the three wave lengths and for several slit widths; it was observed, however, that this favorable result is only obtained if the spectrograph is centered exactly at the band peak with the help of a narrow slit (0.08 mm), even if a larger slit is used for the measurement.

As reported in (7) and (8), the course of the temperature and water vapor concentration had been determined through a flat butane - air flame front. The same has now been done for a hydrogen - air flame. This is of special significance since in this case water vapor is the only combustion product. It is

therefore possible to compare the temperature in the burning zone with the hypothetical temperature which would be reached if the water vapor concentration at the place of measurement would have been produced by adiabatic combustion. It is found that the observed temperature agrees with the adiabatic one at distances 1.5 mm and further downstream of the visible burning zone but exceeds the adiabatic temperature in the visible burning zone by at most 200°C.

In (8) an account had also been given of the rise and decay of the radical radiation (CH, CC, CHO, and OH) and background radiation in the visible and ultraviolet which is observed if a flat butane - air flame front is traversed. The same type of experiments has now been performed with methane - air flames. It was found that, throughout the whole visible and ultraviolet spectrum, the maximum radiation intensity in the flame front is weaker, and that the peaks are less steep, for methane flames than for butane flames. The following table gives the radiation of a 9.80% methane - air flame (producing the highest temperature) at a number of characteristic wave lengths in percent of the radiation of a 3.40% butane - air flame (which also yields the highest temperature) at the same wave lengths, all data referring to the radiation peaks in the combustion zone.

Type of radiation (radical)	CH	CC	CHO	OH	Background
Wave length in Å	4315	5147	3503	3110	4500
Meth. rad. in % of but. rad.	9.2	5.3	7.5	12	29

The background radiation is relatively strong also in the zone downstream of the flame front and makes it especially difficult to measure the radiation due to the radicals mentioned if this radiation is weak. As to the relative change with composition and distance from the flame front, the radiation emitted by the two hydrocarbon flames shows great similarity. For the methane flame, CHO- radiation can be ascertained at all compositions only up to 1/2 mm behind the flame front; for a lean flame and the flame yielding maximum temperature, the CH- and CC-radiation is observed over 1 mm, and the OH- and background radiation over about 45 mm. In rich methane flames, the CH-radiation is still measurable at 14 mm behind flame front, the CC-radiation at 24 mm, and the OH- and background radiation at about 30 mm (compare 8). A more detailed study of the radiation decay is under way.

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INVESTIGATION OF FLAME PROPAGATION AND STABILITY WITH PARTICULAR REFERENCE TO THE INTERACTION BETWEEN FLAME AND FLOW

Cornell Aeronautical Laboratory, Inc. - Phase 2

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Introduction

This investigation is primarily concerned with mutual interactions between flow disturbances and flames. The experimental studies make use, among other techniques, of photographic and motion picture methods for observing combustion wave structure in the presence of artificial or spontaneous flow disturbances, comprising fluctuations of a more or less random nature as well as pipe resonance oscillations and pressure waves. Additional experimental methods include oscillographic recording of pressure and radiation transients, use of ionization probes for timing of flame propagation and study of turbulent flames, and smoke tracer techniques of flow visualization. Concurrently, the interaction of flow disturbances with flames is being studied by methods of small perturbation analysis.

Discussion

Problem 2R20 - Interaction Between Flame and Flow. Work during the past period has been mainly concerned with further development of the slot-burner method for studying combustion wave instability (1) (2). An electric heater with thermostatic control was incorporated in the cooling system of the burner, in order to keep the temperature of the cooled parts high enough for avoiding condensation of water vapor from the burned gases. No measurable effect of cooling water temperature on average cell size could be detected over a range of 20°F.

A series of measurements of average cell sizes has been carried out with butane-air mixtures, varying fuel-air ratio, flow velocity and slot width. The results were in general fairly independent of flow rate and slot width; discrepancies occurred only for small flow velocities close to flash-back conditions.

The data showed, however, considerable scatter that could be traced to two entirely different causes. One was the lack of sufficient accuracy of the flow-metering system. It was therefore decided to use a thermal conductivity cell for measuring mixture composition more accurately than hitherto possible on the basis of flow-meter readings. This device is now being installed and calibrated. As an additional safeguard, the possibility of determining composition by means of a photoelectric bridge sensitive to flame

color changes is being investigated. Moreover, in order to enable more accurate setting of flow rates and to avoid flow fluctuations, precision pressure regulators are being installed in the air and fuel systems.

The other cause of data scattering was found to be inherent in the slot-burner method itself. With some runs, individual cell sizes deviated only little from their average value and were distributed randomly along the slot. Quite frequently, however, under only slightly different conditions, individual cell sizes varied appreciably and in a systematic fashion; regions of predominantly small and predominantly large cells were then distributed along the slot, sometimes symmetrically and sometimes asymmetrically. This phenomenon was presumably caused by minute variations of the flow pattern.

Instead of attempting to eliminate this defect by redesign of the burner, a new approach to the problem of cell size measurement was tried. It had been noted that under conditions of uneven cell size distribution, a non-steady state often existed in which new cells were periodically created in regions of larger-than-average size and destroyed in regions of smaller-than-average size. Preliminary measurements showed that both the maximum cell size just before creation of a new cell by splitting, and the minimum size, just before disappearance, were functions of mixture composition alone and were subject to appreciably less scatter than average cell size.

Instead of avoiding the non-steady state, it was therefore artificially enhanced by means of a thin metal plate that was placed so as to distort the flow pattern in the central portion of the slot slightly. This portion of

the flame became thereby one of large cell sizes and continuing cell creation, while excess cells disappeared in regions of small size about halfway between the edges of the disturbance plate and the slot ends. The rate of cell creation and disappearance could be set at any desired value by adjusting the position of the disturbance plate.

In order to allow accurate and objective measurements of maximum and minimum cell sizes, the movie technique thus far used for recording flame structure is being replaced by continuous strip recording, using the Fairchild Oscillorecord Camera. Since, with this method, certain composition ranges gave insufficient contrast when using direct photography, the shadowgraph method is being adapted for this work.

The measurements carried out thus far have confirmed the initial result that the extreme values scattered less than the average and were independent of flow rate and slot width. In addition to this experimental advantage, there is, moreover, a theoretical reason for selecting minimum cell size as the significant quantity, since linearized stability analysis (3) yields the latter rather than the average value.

Previous theoretical work on flame-flow interactions had been restricted to stability analyses concerned with the fate of an initial distortion of the combustion wave in the absence of subsequently imposed disturbances. A related but somewhat different problem is that of the steady-state response of the combustion wave to a continuing disturbance. This is of interest in connection with effects of artificial periodic disturbances on laminar

flames (4) (5) and particularly with the effect of random disturbances responsible for flame turbulence.

As a first step in the analysis of this problem, a linearized treatment of the interaction between a plane flame front and a plane sinusoidal shear wave has been started. This study is being carried out in analogy to that for shock wave-vorticity interaction (6) (7), but differs from the latter, owing to the presence of a potential flow solution upstream of the flame front, and the onset of spontaneous instability beyond a certain minimum wavelength of the disturbance. A brief discussion of the solution for the special case of normal intersection of shear wave and flame front has been published (8). Work is continuing on the case of oblique intersection.

Problem 2R21 - Measurement of Turbulence Parameters in Flames. This problem has been inactive during the past period.

Problem 2R22 - Study of Combustion Phenomena Related to Pulsating Flow Jet Engines. A shock tube has been designed and built for the purpose of studying the interaction of shock waves and flame fronts. Preliminary experiments with this device will begin shortly.

Notes and References

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RESEARCH ON FLAME AND IGNITION PHENOMENA

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Phase 1

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Introduction

The program is designed to advance fundamental knowledge of the combustion characteristics of explosive gas mixtures. It is divided into three interrelated projects dealing with (1) flames in turbulent flow; (2) ignition by electric sparks; and (3) burning velocity measurements in laminar flames.

Discussion

In the study of turbulent flames a hitherto unknown stage of development of turbulent flames was observed which large, high velocity flames tend to approach. In this fully developed stage the scale of the flame-generated turbulence becomes of the same magnitude as the thickness of the combustion wave. Under these conditions the laminar burning velocity is greatly increased because the combustion wave surface becomes so finely wrinkled that neighboring surface elements influence each other. This is analogous to the situation at the tip of a Bunsen burner.

Minimum ignition energies of a number of hydrocarbon mixtures were found to decrease moderately with an increase of temperature from room temperature to 75° C.

In the work on spark calorimetry and electric characteristics of ignition sparks it was necessary to further develop and improve the experimental apparatus. The instrumentation is now ready for use in systematic studies.

In the work on burning velocity the area of agreement between the bomb method and the slot burner method has been increased by additional data at low pressures. A slight pressure dependence was noticed for certain mixture compositions. The problem of pressure dependence is under further investigation.

Problem IR1 - Measurement of Flame Turbulence and Study of Low Pressure Turbulent Flames; Interpretation. The theory of turbulent flames is based on their structure, therefore the experimental observation of the structure of turbulent flames was extended into regions of higher flow velocity and to flames burning at reduced pressure. For this purpose a schlieren optical system was built with 16-inch diameter mirrors. Schlieren photographs were taken from natural gas-air flames up to an approach flow with Re = 500,000. These pictures are similar to the ones taken at lower flow velocity, but the structure of the flame appears to be finer grained. Also the turbulent boundary between the hot combustion gas and the cold surrounding air renders an analysis of these photographs more difficult than at lower speeds. Therefore a new technique was tried for the observation of the combustion wave by mixing ammonium chloride smoke into the unburned mixture. This smoke disappears sharply at the combustion wave, and the flame appears on a flash photograph as a solid body bounded by the instantaneous combustion wave.

The first electronic probe method was also applied to the study of higher velocity flames. The probability density distribution of the instantaneous position of the combustion wave approaches very closely the normal probability distribution even at high flow velocities, indicating that the structure of the turbulent flame remains substantially unaltered as the flow velocity is increased. Measurements of the scale of the turbulence by this probe show definitely that the scale of turbulence decreases as the turbulence intensity increases.

Methods are under development to measure the turbulent burning velocity by the electronic probe. Preliminary results indicate that the measured turbulent burning velocity is higher than the value calculated from the normal burning velocity by taking into account the flame-generated turbulence. This result becomes understandable from the observation that the scale of turbulence becomes comparable with the thickness of the combustion wave in these high velocity flames. At such small scale of turbulence the proximity of adjacent portions of the combustion wave can lead to very substantial increase of the laminar burning velocity. Further measurements will be carried out for a full analysis of this phenomenon.

Work on the second electronic probe, designed for the measurement of turbulence intensity of turbulent flames, was continued.

Flow fluctuations, which existed in the low pressure system, were eliminated, and steady laminar and turbulent flames were produced down to 1/10 atm. abs. pressure. A schlieren optical system for the study of these low pressure flames is being assembled.

<u>Problem IR2 - Measure and interpret spark ignition energy as a function of initial pressure, temperature, velocity; study effect of spark ignition characteristics and the mode of spark energy dissipation</u>. Minimum ignition energies and quenching distances were measured for hydrogen-air, acetylene-air and methane-oxygen mixtures at various temperatures, in the range between 21 and 75° C. Above 75° C. difficulties were encountered with the apparatus.

It is planned to extend these measurements to higher as well as to lower initial temperatures.

Work on spark calorimetry was continued, with the aim of measuring accurately the spark energy dissipated in the gas between the electrodes. The rebuilt and improved spark calorimeter was used for this purpose. In some experiments erratic breakdown voltages were observed which were probably caused by corona spurts; therefore a transparent bomb was constructed of polystyrene to permit the visual observation of the spark and any preceding corona discharge. To improve the pressure records the oscilloscope was triggered by electromagnetic radiation from the spark and the signal was applied through a delay line. With the improved apparatus measurements were carried out in xenon. The results indicate the presence of some disturbing dynamic effects. To eliminate these some modifications are being carried out on the calorimeter.

The instrumentation for the recording of voltage and current characteristics of small electric sparks has been completed. Spurious signals and other disturbances were eliminated and reliable synchronization was obtained between voltage and current curves. The energy computed from the integration of voltage and current curves was found to agree within a few percent with the energy stored in the condenser. The time resolution of the apparatus is in the order of 10^{8} sec. Work is in progress to apply this apparatus to the study of low energy sparks, such as are capable of igniting explosive mixtures.

Problem IR3 - Precision Determination of Standard Burning Velocity: Comparison of Bomb and Slot Burner. The objective of this program is the study of laminar combustion wave propagation, the development of sound methods for measuring burning velocity, and the collection of data on burning velocity and flame quenching.

The measurement of normal burning velocities as a function of the pressure was continued using both the spherical bomb and the slot burner method. Representative results are tabulated below:

Measured by the spherical bomb method

Pressure, cm.Hg	Burning velocity, S_u, cm./sec. from pressure record	from flame record
	Stoichiometric ethylene-oxygen-argon	
76	127.8	128.1
38	122.6	123.4
	Stoichiometric ethylene-oxygen-helium	
76	191.8	192.6
38	183.7	184.9

Measured by the slot burner method

Pressure, cm.Hg	Burning velocity, S_u, cm./sec.
Stoichiometric propane-air	
76	37.0
38	41.0
25.3	39.9
Stoichiometric ethylene-air	
76	64.5
38	64.5
25.3	64.5

The data found by the burner method on ethylene-air mixtures agree well with the data obtained by the spherical bomb method and reported in the previous semi-annual report. The experiments with helium and argon show that the substitution of helium for argon increases the normal burning velocity considerably. This behavior has already been noted previously by other investigators, but the data reported here are probably the first reliable data on record.

The data show that for these particular mixtures the burning velocity decreases somewhat with decreasing pressure. Pressure dependence of the burning velocity was also noted in nonstoichiometric hydrocarbon-air mixtures. These data require further confirmation and are therefore not reported at this time.

Problem IR4 - Study Mechanism of Flame Stabilization for Fuel Jets and Flames in Ducts; Interpretation. This problem has been inactive in the report period.

MINIMUM SPARK IGNITION ENERGY AND THE SOURCE OF IONIZATION IN FLAMES

Experiment Incorporated - Phase 1

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Introduction

This investigation is concerned with obtaining a more detailed picture of the mechanism of ignition of gaseous mixtures by electric sparks. Thus, the effect of initial temperature on the minimum spark ignition energy and quenching distance has been studied, and the effect of isotopic hydrogens on ignition of carbon monoxide-air mixtures is now being examined. An additional objective is to determine the nature and source of ions in flames by utilizing Langmuir probes. The experimental procedure and a discussion of the method employed to determine the ion concentration at a given point in the flame are to be found in references 1 and 2.

Discussion

Problem 1R1 - Minimum Spark Ignition Energy. The study of the effect of initial temperature on minimum spark ignition energy and quenching distance has been completed and is being prepared for publication.

Experiments have been undertaken to determine the effect of water and deuterium oxide upon the minimum spark ignition energy of carbon monoxide-air mixtures. Thus far the ignition energy has been obtained at one atmosphere and 25°C for 1 mol percent water as a function of equivalence ratio, ϕ, (Stoichiometric air-fuel ratio divided by actual air fuel ratio). The minimum ignition energy occurs at $\phi = 1.6$ where $H = 2.5 \times 10^{-4}$ joules.

Problem 1R2 - The Source of Ionization in Flames. Measurements of ion concentration in a flat flame employing propane-air mixtures has continued. A study of the effect of probe material and probe diameter upon the results has been essentially completed. Evidently differences in peak ion concentrations are independent of the probe material (Pt, Pt-40% Rh, nichrome) or size (0.0020 - 0.0045 inches in diameter) within the normal variation from run to run which is reasonably large. However, the result with Pt-40% Rh probes were most consistant while those for nichrome probes showed the most variation.

In order to obtain a sufficiently stable flame for rich mixtures which could be probed it was found necessary to stabilize the flame on a 5 mesh screen. Experiments for lean mixtures demonstrated that the screen lowered

the ion concentration and increased the thickness of the ionized region, although these effects were not disturbingly appreciable. A lean mixture, $\phi = 0.47$, $T_b = 1400^oK$, gave a maximum ion concentration of 8.5×10^8 ions/cc; a rich mixture, $\phi = 1.58$, $T_b = 1910^oK$ gave a maximum ion concentration of 12.5×10^8 ions/cc. The peak ion concentration for rich mixtures was displaced downstream approximately 1 mm from the relative position of the peak for a lean flame with respect to the maximum temperature. When rich mixtures were burned on the Powling flat flame burner (without the stabilizing screen) cellular structures suddenly developed with any slight disturbance in the flame.

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HIGH OUTPUT COMBUSTION

Massachusetts Institute of Technology - Phase 1

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Introduction

The studies made under this program include investigation of the mechanisms involved in the preparation of fuel-oxidant mixtures for burning, the stabilization and propagation of flame through these mixtures in high capacity combustion systems, and thermal radiation from such flames.

Discussion

Problem 1R2a1 - Flame Stabilization by Bluff Objects. The main subject of investigation in this period was determination of the blow-off limits of propane-air flames when the boundary layer separating from the stabilizer was con -

trolled by suction through slots at the trailing edges of the stabilizer previously described (1). For each run the stream velocity of propane-air mixture in the combustion chamber, and the rate of boundary layer withdrawal were maintained constant. The propane feed rate was then varied until blow-off occured. The ranges of variables covered were as follows:

Main stream velocity: 80 - 180 ft/sec

Rate of boundary layer withdrawal: 0.02 - 0.08 lb/min

Air-fuel ratio: 8 - 24 lb air/lb propane

When blow-off was approached slowly, results were reproducible. With fuel-rich mixtures, blow-off was accompanied by pressure surges, and the data were less reproducible than for the smooth-burning lean mixtures.

At constant stream velocity the change in stability limits due to boundary layer withdrawal was small. As the suction rate was increased beyond the amount calculated to be required for complete withdrawal of the boundary layer, the fuel-air composition at blow-off approached a constant value. Presumably this indicates that the amount of fluid drawn through the slots effectively removed the boundary layer but was not large enough to affect the bulk flow.

For fuel-lean mixtures, removing the boundary layer required a shift to richer mixtures for stability. For fuel-rich mixtures, the shift was again to richer mixtures at stream velocities less than 140 ft/sec, but at higher stream velocities, the shift was to slightly leaner, and then to richer mixtures as more boundary layer fluid was removed, the overall effect being a shift to the rich side after complete withdrawal of the boundary layer. Thus,

in the case of a fuel-lean flame, the theoretically complete removal of boundary layer markedly decreased the blow-off velocity. In the case of a fuel - rich mixture, smaller increase in blow-off velocity followed boundary layer removal.

In another series of experiments either air or propane was blown into the boundary layer through the trailing-edge slots. As expected, for a fuel - lean mixture, the stability was decreased by increasing amounts of air blown into the boundary layer. For a rich mixture, the flame stability was increased markedly when air was blown into the boundary layer, but the flame was accompanied by wild surges and pulsations near blow-off, and therefore a sharp stability limit could not be established. When propane fuel was blown into the boundary layer, a stable pilot flame was obtained, even with the propane concentration in the main stream reduced to zero.

<u>Problem 1R2b3 - Combustion of Oil Drops</u>. The present technique consists in projecting a beam of uniform oil drops from a disc atomizer upwards into an almost isothermal electric furnace, allowing the drops to follow their natural trajectories inside the furnace and out through its bottom. Flame is extinguished as the drops leave the furnace, and the weight of the residue is compared with that of the original. Drop residence times are measured by recording photoelectrically the instants of entry and exit. Operating difficulties described previously have been overcome by equipment modifications, and satisfactory drop combustion data have been obtained during this reporting period.

A steady stream of oil drops can be produced for a period of one to two hours, and newly added heating coils permit the atomization of fuels which are solid at room temperature. The atomizer mounting now permits altering drop trajectories to extend the range of residence times.

With 200 drops per minute projected into the furnace, roughly ten exit pulses are obtained in about 40 seconds, the remaining drops scattering out of the exit light beam. A weighable residue can be obtained in a sampling time of from 5 to 10 minutes. It is possible to identify corresponding entering and exit pulses, thus to measure the residence time of drops in the furnace, and to estimate the scatter of residence times.

Three types of samples are collected in the extinguisher, each requiring a special technique. Dry, light residues are caught on a culture disc and transferred to a small pan for counting and weighing. Sticky, viscous residues are caught on a rotating tared sheet of aluminum foil; rotation distributes them over the foil and thus facilitates counting. Wet, low viscosity residues are caught and frozen on cooled, rotating aluminum foil.

Experiments to date have been made with a residual fuel oil, Aruba Production, (Standard Oil Co. of New Jersey). Furnace temperatures were 900, 1000, and 1100° C and initial drop diameters were roughly 350, 400, 500 and 600 μ.

The typical history of an oil drop in the furnace may be divided into three parts. The first stage corresponds to preheat time, during which

there is negligible change in weight and no flame is observed around the drop. The second stage corresponds to vaporization of the drop surrounded by a flame, and the residues rapidly become more viscous and smaller. A third stage, with slow change in weight, corresponds to the heterogeneous combustion of fluffy carbon residues. The break point between these last two portions of the curves occurs where the residue weight is 5 - 10% of the original and may be related to the asphaltene content of the oil. In no case were cenospheres obtained, presumably because the temperatures were too high.

The data point up certain limitations of the experimental approach. The 500μ drops were the easiest to produce with the disc atomizer and the Aruba oil; they had the maximum range of projection and residence times. With larger drops there was greater scatter of data, presumably due to the increase of drop diameter relative to the size of the furnace exit and entrance slits. With smaller drops, it was impossible to reduce the residence time sufficiently to obtain low degrees of combustion. The equipment is best suited for experiments with drops of 400 to 600μ diameter, although it might be possible to investigate larger sizes by widening the defining slits and using a larger atomizing disc. The 900 - 1100°C range of furnace temperatures reported here is the best for investigation with this equipment and Aruba oil. Lower temperatures would reduce the investigatable portion of the combustion pattern for larger drops; higher temperatures would reduce that for smaller drops.

The effect of the flame envelope on the rate of vaporization was investigated for 500μ drops at a furnace temperature of 1000°C, by comparing data

for drops in furnace atmospheres of air and of nitrogen. In tests with the nitrogen atmosphere some unobservable flames may have been produced by oxygen swept into the furnace by the drops, so these results may be quantitatively less reliable than the air data. Comparison of the data shows that presence of the flame more than doubles the vaporization rate of the oil. It is interesting to note that at the lower rates of vaporization in a nitrogen atmosphere at 1000° C or in an air atmosphere below 800° C, cenospheres were produced.

Based on these data a clear picture of the combustion process can be formed. During preheating both convection and radiation raise the surface of the oil drop from room temperature to its lower boiling point. During vaporization the surface liquid boils off at a rate dictated by radiant heat input from the flame envelope. Calculations based on the work of Mickley et al (2) have shown that even for these small droplets, the convection heat transfer coefficients are reduced to a negligible value in the presence of the high rate of mass transfer encountered here. Finally, the rate of heterogeneous combustion is presumably determined by the rates of diffusion of the gases to and from the carbonaceous surface.

Quantitative discussion of these data must await more detailed information about the Aruba Production oil. The solution of the differential equation for the preheat regions of the curves is straight forward, and preliminary results show good agreement. The vaporization portion of the curves is being theoretically investigated as a problem in heat transfer to a spherical surface

from which vaporization is ocurring.

An investigation is now under way on the combustion of pure hydrocarbons, with a view to determining what chemical and physical properties of the oil are important in the problem. The work is being confined to a single furnace temperature of 1000° C. It is expected that the important oil properties are boiling point, determining the preheat time; carbon-hydrogen ratio and enthalpy of vaporization, determining the rate of vaporization; and for oil mixtures, asphaltene content, determining the initiation and rate of heterogeneous combustion. A series of hydro-carbons is being tested to determine the first two of these effects.

<u>Problem 1R3a - Sampling of Gas Streams Having Time-Varying Density</u>. Analysis of the behavior of sampling probes used in unmixed gaseous streams has nearly reached the stage of numerical computations.

All of the studies mentioned in the last semi-annual progress report have been completed analytically, i.e., equations have been set up and solutions (in the form of sets of algebraic equations) found.

Of primary interest is the equation which expresses error to be expected in the composition of samples collected using a given probe. This expression shows that the time phase relationship between velocity and composition variations (in the fluid actually entering) has a direct influence on the error. If these velocity and composition variations are in phase, the error is pronounced, while if the variations are 90° out of phase, the error is zero.

This may be seen by noting that, under the latter conditions, first high, and then low density material enters the probe during the high-velocity half of the cycle, and then low and high density material enter during the low-density period. Therefore, when the velocity and composition are exactly 90° out of phase, the high and low-density components are collected in the proper proportions even though velocity fluctuations persist at the tube inlet.

Study of the expressions for velocity variation in the fluid (actually entering the sampling probe) as a function of stream properties and probe resonance characteristics shows that the probe internal damping is a major source of error-producing phase shifts. Consequently, considerable effort has been directed toward developing analytical expressions which describe the dissipation forces acting in the system.

It is expected that the results of the numerical computations not only will give considerable insight into the problem of selecting suitable probe proportions, but also will indicate which of several simplified expressions may be used as probe design equations.

Problem 1R3b - Application of Infra-Red Spectroscopy to Combustion Studies.
For the use of personnel in this laboratory an instruction manual for quantitative analysis of gaseous and liquid mixtures with the Perkin Elmer Model 12c spectrometer has been prepared. Emphasizing techniques suitable for analysis of fuels and combustion products likely to be encountered here, detailed schemes have been set up for analysis of ten gaseous mixtures. The experimental application of one of the schemes, for analysis of mixtures of propane,

carbon dioxide, carbon monoxide and nitrogen, has been completed. The calibration curves obtained are intended for use in another project in the laboratory.

In this case a judicious choice of absorption bands enables determination of the mixture composition without solution of simultaneous equations, as is required for many analyses. The experimental procedure consisted of preparing a series of binary mixtures of known composition of nitrogen and each of the other gases and measuring the optical density of each mixture at the wave length where only one of the components has a strong absorption band. The carbon dioxide absorption band at 14.98 micron was choosen for the CO_2 - N mixture; the carbon monoxide absorption band at 4.65 micron for the CO - N_2 mixture; and the propane absorption band at 9.3 micron for the C_3H_8-N_2 mixture. The results were plotted in terms of optical density vs. composition for each of the binary mixtures and the points were found to fall on fairly smooth curves.

After the curves for the binary mixtures had been completed, quaternary mixtures composed of the above gases of various known compositions were prepared and the optical densities at each of the wavelengths mentioned above were measured. The gas compositions corresponding to these densities were then read from the previously determined curves for the binary mixture. The results thus obtained were found to have an average error of about 3% for each of the three components in the mixture. No attempts have yet been made to establish correction factors for the quaternary mixtures.

Problem 1B4c - Investigation of Chemically-Controlled, Unconfined, Unpremixed Flames. The aim of the investigation is to study the influence of chemical kinetics on the length of unconfined, unpremixed, vertical flames. The independent variable is the gas velocity at the burner port. It has been found that flame length is controlled at low port velocities by laminar interdiffusion of fuel and air, at higher velocities by turbulent mixing, and at very high port velocities, presumably by the chemical kinetics of the combustion reaction.

It was suggested in the last report that pairs of gaseous fuel mixtures should be compared whose physical properties, viz. the average molecular weight (M_n), stoichiometric air requirement (c_T), ratio of reactants to products for combustion with stoichiometric air (α_T) and heating value (ΔHc) are identical, but whose chemical properties, and hence whose mechanism of combustion, are likely to be different.

A number of pairs of equimolar binary gas mixtures partially fulfilling these requirements was proposed. By a suitable cross-combination of gas mixtures from two pairs, the heating values of the resultant mixtures can be made equal. Inspection of Table III of the last report shows that a combination of the pairs 5 and 7 is particularly favorable, not only from the point of view of the price and availability of the fuels, but also in that the resultant mixtures contain three rather than four different constituents.

Properties of Equimolar Mixtures

Mixture	Symbol		c_T	α_T	M_m	ΔH_c kcal/gmol
5a	CH_3OH	H_2	0.173	1	17	109.69
5b	CH_4	H_2O	0.172	1	17	95.88
7a	CO	H_2O	0.454	1.13	23	33.82
7b	CO_2	H_2	0.454	1.13	23	28.90

A mixture of 5a and 7b having mol fractions of 0.500 H_2, 0.1314 CH_3OH and 0.3686 CO_2 will have the same values of M_m, C_T, α_T, and ΔH_c as will a mixture of 5b and 7a having mol fractions of 0.500 H_2O, 0.1314 CH_4 and 0.3686 CO. The molecular configurations, and presumably the combustion characteristics, will be different.

Construction of the apparatus for fuel feed and mixing has been completed and preliminary runs have been made. The burner nozzle has a parabolic longitudinal cross-section to give a flat velocity profile at the port A pilot burner consisting of a copper ring with 1 mm holes surrounds the burner port. The research cell is separated from the control area by two wooden panels. One of these is removable and contains an observation window through which the flame measurements are made. The other panel accommodates the manomenters, pressure gauges, flow control valves, pilot control and the quick shutoff handle.

Preliminary measurements were carried out to study the technique of mixing gases and to make flame length and flame breakdown measurements. These

measurements of hydrogen flame lengths showed agreement with values obtained by Hawthorne (3).

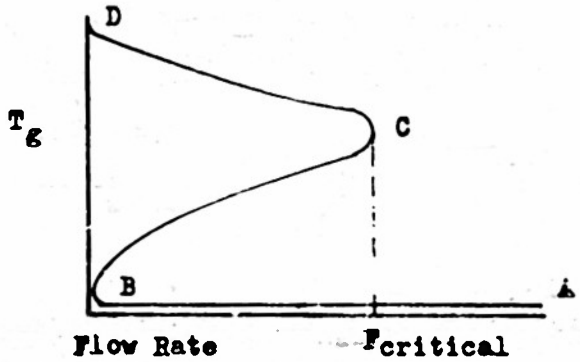
Problem 1R4c2 - Chemical Limitations on High Output Combustion - In most combustion chambers, time required for mixing fuel, oxidant and free radicals limits combustion. As mixing improves the importance of the chemical reaction rate increases until, in the limit, it alone may control the rate of combustion.

The purpose of this investigation is to determine the approximate values of constants which characterize the chemical rate of combustion so that the output of chemically-controlled combustion chambers and the performance of piloting devices may be estimated. In the course of determining these constants, it is hoped to determine the relative importance of molecular configuration versus atomic composition of fuel molecules.

The proposed experimental method involves feeding premixed air and fuel to a spherical combustion chamber through six entrance ports located on the surface of the chamber at the extremes of three mutually perpendicular diameters. Thirty-two symmetrically located exit ports will be provided for the hot burning gases. It is planned to inject the feed gases with sufficiently high velocity to provide intimate mixing with the gases in the sphere immediately after entry so that the exit gases will be nearly representative of those at any point in the sphere.

The behavior of such an high output combustion chamber is described by the

material and energy balances for a steady-state flow process, together with a simple formulation for the kinetics of the overall combustion reaction. Simultaneous solution of the material and energy balances and the rate equation results in an expression relating the temperature, T_g, of the gases in the sphere to the feed rate to the sphere for any particular air-fuel ratio, fuel kinetic characteristics and heat losses. A similar derivation is given by Longwell, Frost and Weiss (4) for stability of bluff-body stabilized flames. The expected shape of the curve of T_g vs flow rate is shown below:



Of the three distinct portions to this curve, B - A represents the slow chemical reaction of unignited gases and may be regarded as trivial. Temperatures along B - C may be considered as ignition temperatures and operation at any point on B - C is unsteady; perturbation of operating conditions will cause either a rise in temperature until line D - C is reached or a decrease in temperature and blowout, with the gases passing through the combustion chamber essentially unreacted (B - A). Line D - C is the stable line of operation for ignited gases. Point C is of special interest. If the combustion chamber should be operating on line D - C and the flow rate be monotonically increased, the flame would blow out at point C and proceed along line B - A after

$F_{critical}$ is passed.

Measurement of Tg as a function of feed rate should yield sufficient data for the establishment of pseudo reaction rate constants in terms of any simple assumed overall reaction between fuel and air. Such measurements will be carried out at various air-fuel ratios and at atmospheric and subatmospheric pressures.

To contrast the effects of molecular configuration against empirical molecular composition, six fuel mixtures have been tentatively selected for investigation. Three of the mixtures have the identical empirical composition, enthalpy of combustion, and adiabatic flame temperatures, respectively, as do three other mixtures. However, in a given pair, the structure of the molecules constituting one mixture is substantially different from that of the other mixture. If these two mixtures should yield dissimilar characteristic rate constants, then it could be concluded that the combustion reaction rate is a function of the molecular structure as well as the empirical composition of a molecule.

The work to date has included some design of equipment as well as theoretical study of the problem. In addition the chosen fuel mixtures have been tested for explosiveness under feed conditions and have been found safe to handle.

Problem 1R5b - Carbon Deposition from Jet Fuels. During the reporting period extensive tests have been made of the carbon-forming tendencies of pure hydrocarbons and mixed fuels with the bench-scale combustor described in the last

report, and an empirical equation has been found to correlate the results.

Tests in which fuel droplet size was varied showed that smaller carbon deposits resulted with use of smaller drops. Tests with JP-4, a wide-cut jet fuel, showed that for any given temperature of the carbon deposition target there is a point beyond which carbon deposition is not additive, i.e., the deposit tends to burn off after accumulation of an equilibrium deposit. No general statement can be made about the effect of air-fuel ratio, although with many fuels the size of deposits increased with lower air-fuel ratios.

Carbon-forming tendencies of twelve pure hydrocarbons were next determined. These represented straight and branched-chain aliphatics, mixed aliphatics - aromatics, naphthenes, aromatics, an olefin and a cycloparaffin - aromatic, with the boiling points ranging from 173 F (benzene) to 470 F (α- methyl - naphthalene) and the carbon-hydrogen weight ratio ranging from 5.3 (n - heptane) to 13.2 (α- methylnaphthalene). Experiments with each hydrocarbon were run with air-fuel ratios of 40.1 and 60.1 and with droplet sizes of 100 and 250 microns for each ratio. The results showed carbon deposition to be an additive function of carbon-hydrogen ratio and boiling point. An equation which correlates the results is

$$W = \frac{\ln (R - K_1)}{K_2} + \frac{T}{K_3} + K_4 \qquad (1)$$

where: W = weight of carbon deposited,

T = boiling point at atmospheric pressure,

R = carbon-hydrogen weight ratio

and the K's are empirical constants determined graphically from experimental results. The equation is similar to that of Starkman (5) except that it has

one less constant and gives better agreement between prediction and experimental results obtained here.

Experiments with fourteen binary mixtures showed that their carbon forming tendencies could be predicted if in equation (1) the R value used is that of the blend and the T value is a volume weighted average of those of the components. When the carbon-hydrogen ratios of the components are nearly alike, carbon deposit weight is a linear function of blend composition; when R's differ greatly the relation is non-linear, as would be expected in consideration of the logarithmic average of R values. For relatively narrow boiling binaries (50° range or less) predicted and experimental deposit weights were in almost as good agreement as in the case of single-component fuels. With wider differences in the boiling points of components the predicted values were increasingly higher than the experimental.

In addition to blends of the pure hydrocarbons previously tested individually, some experiments were made with binaries of diphenyl and lighter hydrocarbons. Pure diphenyl could not be tested in the bench-scale apparatus because of its high boiling point, but blends containing diphenyl were tried because according to some theories it plays an important part in carbon formation in flames. Tests of diphenyl-benzene and diphenyl-n-heptane blends, however, showed them to behave approximately as predicted by equation (1), with no increased carbon-forming tendency.

The experiments were next extended to multicomponent fuels including three

commercial and three experimental jet fuels, two commercial diesel fuels, two commercial automotive fuels and one tractor vaporizing oil. The predicted carbon-deposit weights were slightly higher than the experimental for fuels with narrow boiling ranges, as was the case with binaries, and considerably higher for wide-boiling blends. There was little difference in the results for jet fuels with and without cracked components. It appears that within limits the carbon deposition of commercial fuels is predictable if the carbon-hydrogen ratio and average boiling point are known and a correction factor for boiling range is applied.

Comparisons have been made between the results of the present bench - scale experiments and the data obtained by others with full- and semi-scale turbine combustors. The data of Wear et al. (6) at NACA represent work with individual hydrocarbons, binary blends and multicomponent fuels in which a 10-3/8" annular combustor was used. The data of Starkmann (5) and co-workers of the Shell Development Co. represent tests of eleven pure hydrocarbons and five multicomponent fuels; a scaled-down, 2-inch, version of a single burner similar to those in multicomponent aircraft turbojets was used. The results of these investigations were fitted with equation (1) and new values of the constants determined. The constants are tabulated below:

	K_1	K_2	K_3	K_4
NACA	+ 14	0.975	500	-3.5
Shell	-4	0.474	120	-3.14
MIT	-3	0.6	120 -180	-2.6

There is good agreement between the NACA experimental results and the equation (1) with NACA constants, considerably more scatter in the case of the Shell results. The radical difference in K_1 values listed above is unexplained to date.

In conclusion, it appears that carbon deposition can be predicted if sufficient experimental data are available to establish the constants in the carbon deposition equations, but that these (especially K_1) may differ widely with different types of equipment and to some extent with operating conditions.

Problem 1R5c - Radiant Heat Transmission in Furnace Enclosures. Work is in progress to devise general methods for predicting radiant heat transmission in furnace enclosures. Although methods are available for calculating the rate of heat transfer in a furnace containing a radiating gas at uniform temperature, it is not possible in general to allow for temperature gradients within the gas mass.

The approach used consists of dividing the gas into cubes, each of which is taken small enough so that it may be considered isothermal. At the same time the bounding walls are divided into elements equal to the faces of the adjacent cubes of gas; these area elements are also considered isothermal.

Let the cubes of gas be designated n_1, n_2, n_3.....and the squares of surface m_1, m_2, m_3.....Since the temperature of any cube of gas, n, or of any surface element, m, will not change with time, an energy balance may be written on each gas cube and on each surface element equating the total energy radiated

by the element to the energy absorbed by it from all other elements in the system. For a cube of gas, n, the energy balance becomes:

$$E_n = \sum_n R_{nn} + \sum_m R_{mn} + Q_B + Q_{C nn} + Q_{C mn}$$

And, for a surface element, m:

$$E_m + Q_m = \sum_n R_{nm} + \sum_m R_{mn} + Q_{C nm}$$

where E represents total emission, R one-way radiation between two elements, Q_m the wall flux through area m, Q_B energy transport by bulk flow of the gas stream, and Q_C energy transferred by convection. In the above equations a double subscript such as mn, nm, mm, or nn indicates the direction of the energy transfer, the first subscript denoting the source of the energy and the second the receiver.

If the system consists of n cubes of gas and m surface elements, consideration will show that the total of n + m equations which may be written will contain as unknowns only n unknown gas temperatures and m unknown wall temperatures or wall fluxes. In principle, therefore, the problem is now simply a solution of a set of simultaneous equations for the desired unknowns, either the temperature at any point in the system or the flux through any wall.

In order to evaluate the various R and E terms in the above equations it is necessary first to evaluate the direct interchange factors between cubes, between squares of bounding area, and between a cube and a square as well as the total emission from a cube of gas. Methods are available in the literature (7), (8) for predicting interchange factors between squares of bounding

area. In this work to date, the emission from a cube of gas and the direct interchange between cubes of gas have been evaluated.

The total emission from a cube of gas in all directions divided by σT^4 within the cube, can be shown to be equal to 4k times the volume of the cube, where k is the absorption coefficient of the gas in question. Because of attenuation, the actual emission is less than this amount and may be set equal to $\phi \cdot 4kV$. Values of ϕ as a function of KL (where L is the length of the cube edge) have been obtained by quadruple graphical integrations and are presented in Figure 1.

The interchange between cubes of gas is much more complicated and must be obtained by an extremely tedious sextuple graphical integration for each value of kL and for each set of values of Δx, Δy and Δz, the distances between cube centers measured along the three coordinate axes. As a simplification, if the distance between cube centers is large and kL is not too high, the cubes may be represented by spheres of the same volume on the same centers. The interchange factors for spheres are obtained much more simply, involving only a double graphical integration. The results for both spheres and cubes may be represented in the form of a factor f_{nn}, the fraction of the total emission from one cube of gas which is absorbed by another cube at a center-to-center distance of r. Figure 2 shows f_{nn} versus r.

Future plans involve the completion of the interchange factors so that numerical solutions may be obtained and compared with data on operation of industrial furnaces.

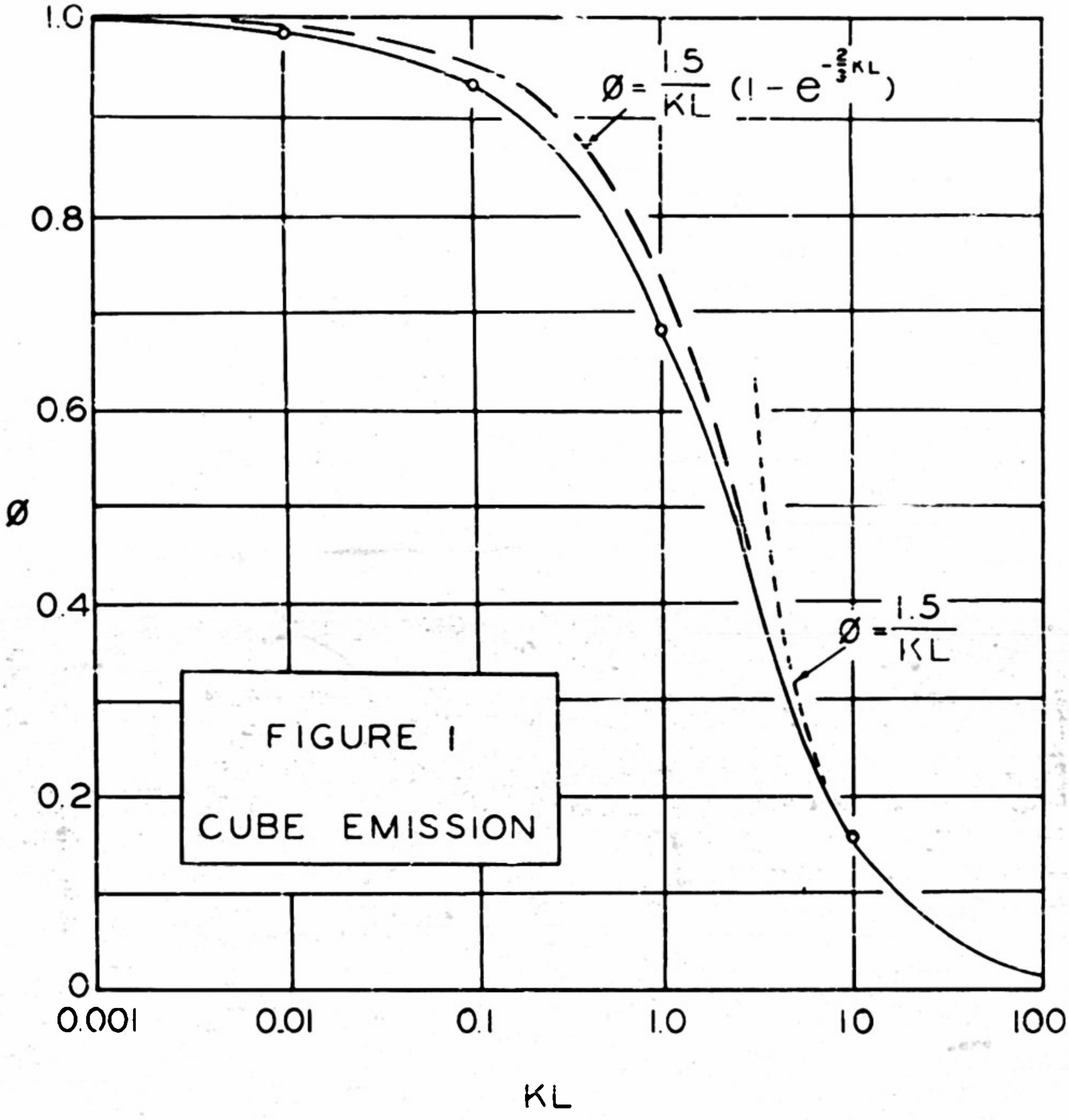


Fig. I. Cube Emission

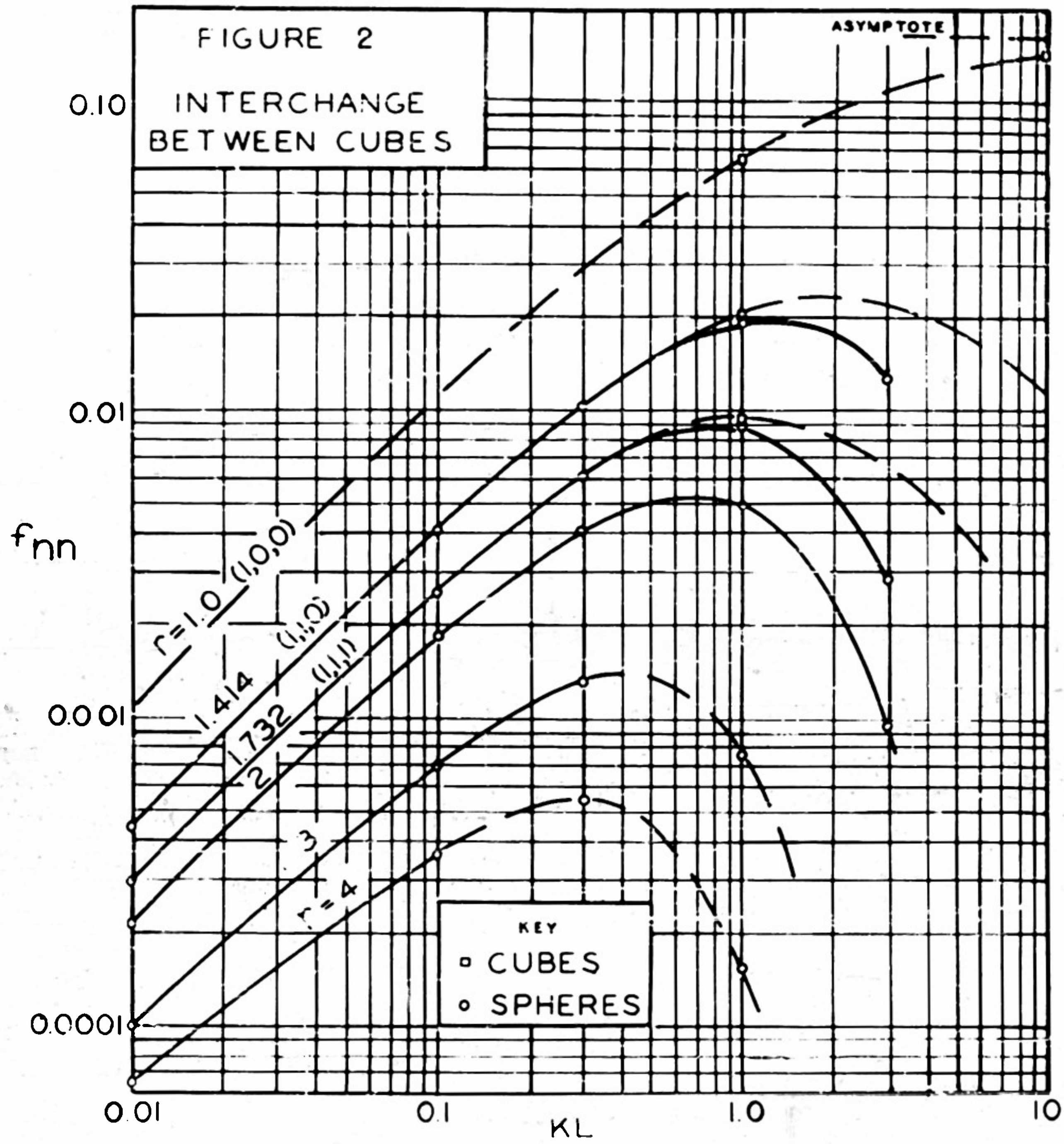


Fig. II. Interchange Between Cubes.

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TURBULENT FLAMES, FLAME STABILITY, AND ROUGH BURNING

Atlantic Research Corporation - Phase 1

A. C. Scurlock, Phase Leader, J. H. Grover, W. P. Barnes

Introduction

This investigation is concerned with gaining a more fundamental knowledge of some of the important variables encountered in modern high-output combustion chambers. Attention is being devoted to the study of (1) the effects of turbulence on flame propagation, (2) the mechanism of flame stabilization on blunt objects in homogeneous combustible gas streams, and (3) resonance and rough burning phenomena in ducts. These studies are being conducted in chambers of both rectangular and circular cross-section using mixtures of air and widely different fuels.

Discussion

Problem 1: The Effects of Turbulence on Flame Propagation. The principal effort during the present period has been devoted to construction of the

apparatus required to test the theory of turbulent flame propagation presented at the "Fourth Symposium (International) on Combustion."(1) The chamber to be used to stabilize a flame in a turbulent stream without introducing shear forces across the flame front has been completed and is ready for preliminary testing. The hot-wire anemometer and compensated amplifier for turbulence measurements are in the final stages of construction - testing of some components is under way.

A paper entitled "Experimental Studies of Turbulent Flames" by A.C. Scurlock and J.H. Grover, reviewing the field indicated by the title is under preparation for presentation at the "Combustion Colloquium" sponsored by the NATO Advisory Group for Aeronautical Research and Development to be held in Cambridge, England in December, 1953.

Problem 2: Mechanism of Flame Stabilization. The study of the mechanism of flame stabilization behind blunt objects in a combustible stream requires investigation of a number of variables which may influence the stabilization process. A better understanding of the phenomena that take place in the eddy region immediately downstream of the stabilizer is of great importance. The study of propagation from this primary flame zone into the main combustible stream, as it is related to rough burning and blow out, is included in Problem 3.

Considerable stability limit data have been accumulated for rod stabilizers mounted in a 1 x 3 inch rectangular duct using city gas, commercial propane, 99.9 per cent pure propane, and hydrogen, with air as the oxidant. The data were taken at the following points:

a. The beginning of a noticeable (to the eye) interruption in the propagation of the flame from the primary zone into the main gas stream.

b. The complete absence of flame propagation from the primary zone into the main gas stream, resulting in a residual flame as previously reported by Scurlock.(2)

c. Complete blow-off of the flame from the stabilizer.

The data points from (a) above are admittedly somewhat subjective, but it is felt that they will be useful in further study under Problem 3.

Data taken to date include:

a. For city gas-air mixtures, complete stability limit curves have been obtained for rods of 0.02, 0.05, 0.1, and 0.2 inch diameter and approach stream velocities from 20 ft/sec to the peaks of the respective curves. For the 0.5 inch diameter rod, data are available in the velocity range of 20 ft/sec to 400 ft/sec, no peak in the curve having been reached.

b. For 99.9 per cent pure propane - air mixtures, complete stability limit curves have been obtained for rods of 0.02, 0.05, and 0.1 inch diameter from 20 ft/sec up, and for rods of 0.2 and 0.5 inch diameter, from 20 ft/sec to 340 ft/sec, no peak being reached for the latter.

c. For hydrogen - air mixtures, the data to date are confined to lean stability limits for rods of 0.013, 0.02, 0.05, 0.1, 0.2

and 0.5 inch diameter, and velocities from 60 ft/sec to 380 ft/sec. No peaks in these data have yet been obtained.

d. The data taken for commercial propane - air mixtures cover a relatively narrow range, their use being restricted primarily to preliminary and check-out runs. The data available show little difference between the commercial and 99.9 per cent pure propane, but it was felt that the use of 99.9 per cent pure propane would give data more reproducible and more easily subject to testing by other workers in the field.

A correlation of blow out velocity (V_{BO}) over some power of the rod diameter (D^N) versus generalized oxidant fraction (O_G)* for city gas - air mixtures was attempted. A value of N equal to 0.18 gave the smallest scatter of the data. Thus, the effect of diameter appears to be much smaller than reported by previous investigators.(2,3) However, even using this optimum value of N, there was enough scatter in the data to show that additional parameters are needed to correlate stability limits.

The effect of rod diameter on the stability limits for 99.9 per cent pure propane - air mixtures was very similar to that for city gas - air mixtures. However, there was a marked shift of the stability limits to richer mixtures with decreasing rod diameter for propane.

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*The generalized oxidant fraction, O_G, is defined as:

$$O_G = \frac{\text{Oxidant}}{\text{Oxidant + Oxidant equivalent of fuel}}$$

Two other items of interest are apparent from the data taken to date:

a. For both city gas and pure propane, at velocities from 20 ft/sec to 80 ft/sec with the 0.02 inch diameter rod, the stability limit curves become narrower with decreasing velocity.

b. The hydrogen-air data taken to date (on lean side only) indicate decreasing stability with increasing rod diameter (the same effect is noted in certain ranges of velocity and O_G for both city gas and propane).

Further correlation of all data with more fundamental flame parameters, such as laminar flame velocity and quenching distance will be undertaken shortly. A rectangular-nozzle burner has been constructed for measurement of laminar flame velocity. Quenching distance will be measured using flat parallel plates and determining the minimum channel width through which flashback can occur when the flow rate is reduced to zero.

In order to determine the flow pattern involved in flame stabilization, several techniques are being employed. Some data have been taken on the longitudinal pressure distribution from two diameters upstream of the stabilizer to ten diameters downstream for straight, converging, and diverging ducts. Further work is being done to extend the range of measurement and to determine if there is any appreciable pressure gradient across the flame front.

In addition, an optical bench has been constructed to permit shadow and Schlieren observation and photography (including high-speed photographs) of the flame zone, and a particle-tracking technique will also be applied in attempting

to deduce the flow phenomena in the neighborhood of the stabilizer.

Problem 3: Resonance and Rough Burning. Resonance and rough burning phenomena are considered to be the result of pressure and velocity fluctuations initially induced by random fluctuations in the percentage completion of combustion in the duct. Intimately associated with this problem is the effect of tailpipe length (distance from stabilizer to duct exit) on flame stability. Flame blow out data are now being accumulated using a 0.5 inch spherical stabilizer in a 1.5 inch diameter circular chamber with a continuously adjustable tailpipe length. Preliminary data indicate little effect of tailpipe length on stability in the range zero to six inches. For tailpipe lengths greater than six inches, however, the maximum approach velocity for stable operation decreases rapidly as tailpipe length is increased.

It is hoped that relationships between the percentage completion of combustion and fluctuations in this quantity, the approach velocity and its fluctuation, the frictional drag (high drag generally reduces roughness) and normal modes of the system, and the resulting reduction in flame stability can be found. The randomness of upstream and flame-generated turbulence may necessitate the use of statistical methods.

Notes and References

1. Scurlock, A.C. and J.H. Grover, "Propagation of Turbulent Flames," Proceedings of the Fourth Symposium (International) on Combustion, held at

Cambridge, Massachusetts, September, 1952. Williams and Wilkins Company, Baltimore, Maryland, 1953, page 645.

2. Scurlock, A.C., "Flame Stabilization and Propagation in High-Velocity Gas Streams," Meteor Report No. 19, Fuels Research Laboratory, M.I.T., May, 1948.

3. Haddock, G.H., California Institute of Technology, Jet Propulsion Laboratory, Report No. 3-24, May 14, 1951.

COMBUSTION STUDIES

Princeton University - Phase 2

R.N. Pease, Phase Leader
W.H. Clingman, F. Falk,
C.C. Schubert, C.I. Tewksbury

Introduction

This phase, which is sponsored jointly with Project Bumblebee, Applied Physics Laboratory, Johns Hopkins University, deals with flame speed measurements and studies of slow combustion. Particular problems which were actively pursued in the last six months include the measurement and interpretation of flame speeds of methane-air mixtures at reduced pressures, and the analysis of reaction kinetics for the oxidation of ammonia, hydrazine and hydrocarbons.

<u>Flame Speeds of Methane-Air Mixtures at Reduced Pressures</u>. A series of measurements of flame speeds for 9.46% methane in air

has been carried out over a pressure range from 250 to 760 mm. using two different burner diameters and several flow rates. The results clearly demonstrate the increase in flame speed from 40.0 cm/sec. at 760 mm. to 65.0 cm/sec. at 250 mm. This result is in general accord with the atom-diffusion picture of Tanford.

Current work is a repetition of earlier measurements with helium and argon replacing the nitrogen of air. An account of the latter is appearing in the report of the Fourth Symposium on Combustion.

<u>The Ammonia-Nitrogen Peroxide Reaction</u>. Ammonia and nitrogen peroxide (a mixture of N_2O_4 and NO_2) react almost instantaneously at room temperature to produce ammonium nitrate, nitrogen and water -

$$2NH_3 + N_2O_4 \longrightarrow NH_4NO_3 + N_2 + H_2O.$$

The reaction has a negative temperature coefficient such that rates are just becoming conveniently subject to measurement at about 200°C and above. Some preliminary measurements at 200° have been made but the scatter is at present too great to allow of a definite statement regarding kinetics. This work is being pursued.

A third paper on the ammonia-oxygen reaction is being prepared.

<u>Oxidation of Paraffin Hydrocarbons</u>. Recent speculation about the oxidation of saturated hydrocarbons stresses the formation of alkyl peroxides as intermediates. Experimentally it is usually found that hydrogen peroxide and its condensation products with aldehydes are present in quantity but there is no completely satisfactory evidence for the survival of alkyl peroxides. With a view to initiating reaction at lower temperatures experiments with ozonized oxygen have been carried out. It is found that reaction is appreciable at as low as 100°C., compared to 250-300° without ozone. However the amounts of product are not in excess of the equivalent of ozone present.

A paper entitled "A Kinetic Study of the Diborane-Ethylene Reaction" has been submitted to the Journal of the American Chemical Society. A paper on hydrazine oxidation is in process of preparation.

INVESTIGATION OF IGNITION LAG OF SPONTANEOUSLY IGNITABLE PROPELLANTS

Purdue University - Phase 9

M. J. Zucrow, Project Director
B. A. Reese, Assistant Project Director
Edward B. Dobbins, Phase Leader

Introduction

The object of this phase is to determine the effects of certain variables on the ignition lag of several hypergolic liquid propellants as measured in an open-cup apparatus and in a small rocket motor. The variables investigated during this period were:

(1) mixture ratio, and

(2) manner of mixing.

The investigations during this period were conducted with the rocket motor apparatus, and for that apparatus the ignition lag is defined as the time interval between the instant of impingement of the fuel and oxidant streams and either the instant that visible light is emitted by the reacting

propellants or the instant that a pressure rise is evident within the rocket motor combustion chamber. The rocket motor apparatus is described in detail in references (1, 3).

Discussion

Experiments reported in reference 2 were concerned with the effect of injection pressure (same values for fuel and oxidizer), the effect of the impingement angle of the propellant streams and the effect of mixture ratio (O/F ratio on the ignition delay of a fuel mixture of 80% furfuryl alcohol and 20% aniline (by weight) oxidized with WFNA, at ambient temperatures (60°F to 80°F). Since the last report, an investigation on the ignition lag of the same propellants has been completed on (a) the effect of varying the fuel injection pressure, with the oxidizer injection pressure held constant at 100 psi, and (b) the effect of varying the oxidizer injection pressure with the fuel injection pressure held constant at 100 psi. The injector for both investigations was designed for an O/F-ratio of 2.75 to 1 when the oxidizer and fuel injection pressure were equal and an angle of impingement of 90°; consequently, the effective O/F-ratio varied during the experiments. The results of (a) are presented in Table I, and for investigation (b) are presented in Table II. The results indicate that for the propellants investigated, and for the range of propellant temperatures employed, the optimum injection pressure for the fuel is that giving the stoichiometric mixture

ratio for the injected propellants. Similar results were obtained when the oxidizer injection pressure was varied, that is, the minimum ignition delay is obtained with injection pressures giving the stoichiometric mixture ratio.

Investigations (a) and (b) also indicate the effect of mixing as well as the effect of mixture ratio on the ignition lag. Injection tests with water indicated definite unfavorable mixing conditions for different propellant momentum rates. When propellant streams having appreciably different momentum rates impinged, the stream having the larger momentum deflected slightly while the low momentum stream atomized completely. For near equal stream momentum rates, impingement resulted in thorough atomization and mixing of both propellant streams. Previous investigation, reported in reference 2, determined that for the conditions where both injection pressures were equal, the ignition lag is a minimum at approximately the stoichiometric mixture ratio, and increases only slightly for other mixture ratio values. The investigations with varying injection pressures described herein demonstrated the combined effects of momentum rates and mixture ratio on ignition lag. The ignition lag at mixture ratios where the pressure on one of the propellants was different from 100 psi was considerably larger than those lags measured under conditions where the pressures were 100 psi on both propellants. Although the results were anticipated, they verify the conclusions deduced earlier on the importance of mixing; those conclusions were based on data obtained from open-cup tests wherein the distance of fall of the fuel stream was varied (2).

No further research activities are planned under Phase 9.

Notes and References

1. Stanley V. Gunn, "The Effects of Several Variables upon the Ignition Lag of Hypergolic Fuels Oxidized by Nitric Acid," A.R.S. Journal, January-February, 1952.
2. Project SQUID Progress Report, 1 October 1952.
3. Project SQUID Progress Report, 1 October 1951.

Table I

THE EFFECT OF FUEL INJECTION PRESSURE UPON THE IGNITION LAG OF 80% FA-20% A REACTED WITH WFNA

(Propellant Temperature 45° to 60°F)

Fuel Injection Pressure (Psi)	Oxidizer Injection Pressure (Psi)	Effective Mixture Ratio O/F	Ignition Delay* (Millisecond)
100	100	2.75	9
80	100	3.[illegible]8	10
68	100	3.34	12
55	100	3.71	13
116	100	2.55	10
125	100	2.46	10 1/2
140	100	2.32	11
164	100	2.15	14

* Based on evidence of pressure rise in combustion chamber (2).

FA - Furfuryl Alcohol

A - Aniline

WFNA - White Fuming Nitric Acid (96.2% HNO_3, 2.2% NO_2, and 1.6% H_2O)

THE EFFECT OF FUEL INJECTION PRESSURE ON THE IGNITION LAG OF 80% FA-20% A REACTED WITH WFNA

(Propellant Temperature 45° to 60°F)

Oxidizer Injection Pressure (Psi)	Fuel Injection Pressure (Psi)	Effective Mixture Ratio O/F	Ignition Delay* (Millisecond)
100	100	2.75	9
68	100	2.27	11 1/2
55	100	2.04	13
455	100	1.85	13
111	100	2.90	10
121	100	3.03	13 1/2

* Based on evidence of pressure rise in combustion chamber (2).

FA - Furfuryl Alcohol

A - Aniline

WFNA - White Fuming Nitric Acid (96.2% HNO_3, 2.2% NO_2, and 1.6% H_2O)

IGNITION CHARACTERISTICS OF FUEL DROPLETS FALLING IN AN OXIDIZING ATMOSPHERE

Purdue University - Phase 8

M. J. Zucrow, Project Director
B. A. Reese, Assistant Project Director
D. A. Charvonia, Phase Leader

Introduction

The object of this phase is to obtain information on the mechanism leading to the ignition of fuel droplets, and to study the effects of the pertinent parameters upon the ignition process. The apparatus employed is discussed in previous Semi-Annual Project Squid Reports. Basically, the apparatus is a means for recording photographically the ignition of fuel droplets falling through the heated decomposition vapors of WFNA.* The combustion phenomenon occurs as follows for the fuels employed: the initial ignition occurs between the fuel and acid vapors in the region above the falling droplet, after which the flame front propagates rapidly downwards, overtakes

* WFNA denotes white fuming nitric acid, HNO_3, concentrations above 96%

the falling droplet, and then, combustion ensues in the fuel vapor region surrounding the falling droplet.

Discussion

Data were previously reported for three fuels, allyl amine, cyclohexene and triethylamine, relating their respective ignition delays to the pertinent parameters, WFNA vapor temperature and fuel temperature. In the interim period data have been taken with the aforementioned three fuels employing fuel droplet size as the parameter. These data are presented in Table I. In addition three additional fuels were investigated; cyclohexylamine, n-propylamine, and diethylamine. The latter fuels were chosen for two specific reasons, (a) they have sufficiently short ignition delays to ignite within the maximum droplet descent time in the apparatus, and (b) they have specific chemical structural differences from the three fuels investigated earlier. A prime factor in selecting the choice of fuels was an attempt to attain an insight into the effects of chemical structure upon the ignition process. The data obtained with the three new fuels relate the ignition delay to the WFNA vapor temperature, fuel temperature, and a new parameter, WFNA vapor velocity. These data are presented in Tables II, III and IV. An investigation of WFNA vapor velocity was instigated when discrepancies were found in the data obtained from experiments where all of the other parameters were maintained constant.

The WFNA flow rate through the reaction was measured and approximate values of WFNA vapor velocity were then calculated; the velocities values should be considered as representative of their order of magnitude.

Attempts to derive a theory for generalizing the experimental results have not been fruitful. It is believed that some of the difficulties arise from the complex nature of the WFNA vapors and to the lack of data on physical properties of the fuels employed. For those reasons, additional experimentation in the current apparatus will be undertaken employing heated air as the oxidizing agent.

Under the continuation of Phase 8 it is proposed to study the evaporation rates of fuel droplets falling freely in heated gaseous environments.

A technical report summarizing the results obtained to date on Phase 8 is being prepared.

TABLE

SUMMARY OF IGNITION DELAY DATA
FUEL DROPS FALLING THROUGH WFNA VAPOR

- to - indicates discernible trend or range of controlled variable

± indicates apparent randomness

Fuel	Temperature °C Fuel	WFNA	Drop size mm.	Corresponding Range of Ignition Delay - Milliseconds Vapor	Drop
I. Effect of Drop Size					
Cyclohexane	19±1	507±2	2.95 to 4.06	84 to 70	90±6
Allyl Amine	"	"	2.82 to 4.20	52±5	61±5
Triethyl Amine	"	"	2.68 to 4.09	28±4	34±4
II. Effect of WFNA Temperature					
Diethylamine	21±1	294 to 546	2.89± .11	25±6	31±7
n Propylamine	"	404 to 546	3.07± .14	72 to 50	109 to 58
Cyclohexylamine	"	421 to 546	3.29± .06	92 to 65	113 to 77
III. Effect of Fuel Temperature					
Diethylamine	21 to 53	507±2	2.89± .11	27±2	33±2
N Propylamine	20 to 45	"	3.07± .14	62±2	80±5
Cyclohexylamine	22 to 88	"	3.29± .06	70 to 48	82 to 61
IV. Effect of WFNA Vapor Velocity	Velocity - Ft/sec.				
Cyclohexylamine	.218 to 3.034		3.29± .06	103 to 55	123 to 70
Cyclohexylamine	.255 to 3.540		"	81 to 41	91 to 54

FLOW AND COMBUSTION IN ROCKET MOTORS

Princeton University - Phase 5

J.V. Charyk, Phase Leader
I. Glassman, A.A. Kovitz

Introduction

Rocket motors offer a convenient means for studying kinetics and interaction of processes in reaction zones by precluding the necessity of measuring values of reaction times of extremely small magnitudes. This is accomplished by establishing a high velocity, steady flow of propellants and thereby transforming such times into easily measurable distances in the direction of flow. Experimentally this distance transformation is achieved by injecting premixed gases through a porous plug into a throatless rocket motor combustion chamber. The complete analysis and experimental procedures have been described in the previous progress report.

Discussion

Construction and installation of the rocket motor and its related equipment and instrumentation were completed during the last period and experimentation begun. The first efforts were directed towards the determination of the one-dimensionality condition in the motor. In the first tests carried out, high mass flow rates of air were injected through the porous plug into the motor in order to investigate the flow conditions set up without combustion. For all the stainless steel porous material available at the time, the pressure drops across the material for the desired flows were great enough to cause deformation of the plug, which contributed to distorted flow profiles. In one instant where a deformed plug was reversed, a fairly uniform turbulent pipe flow profile was approached, but on continuous operation deformation of the plug and poor profiles were again obtained.

While awaiting delivery of more porous, stronger material for the plugs, preliminary combustion tests were initiated. For all the methane air mixtures used and ignition at the rocket exit, it was found impossible to make the flame hold on the porous plug. The flame would position itself at the rocket exit at all times. When ignition was made at the plug by sparking a wire off its face, the flame remained in the combustion chamber, but only for low total mass flow rates. From the experiments reported by Charyk and Matthews (1), it is now believed that enriching the air with oxygen would pre-

vent the higher flow rate flames from blowing off the plug and yet not seriously increase the flash back possibilities. Such oxygen rich runs will be made.

The porous material with the higher strength has recently arrived and, in the extension of the time granted to the phase, efforts will be made to establish the one-dimensionality condition of flow and the possibility of improving the flame holding characteristics of the gas mixtures by enriching the air with oxygen.

Notes and References

1. Charyk, J.V., and Matthews, G.B., "Experimental Studies of Energy Release Rates in Rocket Motor Combustion Chambers", Princeton University Aeronautical Engineering Laboratory Report No. 191, March, 1952.

INDEX BY CONTRACTOR

APPENDIX A

REPORTS PUBLISHED

April 1, 1953 - October 1, 1953

I. PAPERS IN PRINT

Contractor	Title and Author	Identification number	Publisher
Cornell	Three-Dimensional Liquid Analog for the Determination of Temperature Distribution,-G. A. Sterbutzel and J. L. Beal.	CAL-44	Squid Headquarters
Cornell	A Slot Burner Method for Studying Combustion Wave Instability,-G. H. Markstein and L. M. Somers.	CAL-45	J. Chemical Physic
Princeton	Confidential	Pr-20	Squid Headquarters
Princeton	Kinetics of the Non-Catalytic Oxidation of Ammonia: Static Experiments in an Empty Uncoated Silica Vessel,-E. R. Stephens and R. N. Pease	T.R.-47	J. Am. Chemical Society
Princeton	Effect of Water on the Burning Velocities of Cyanogen-Oxygen-Argon Mixtures,-R. S. Brokaw and R. N. Pease	T.R.-48	J. Am. Chemical Society
Cornell	Thrust and Drag,- R. C. Weaterston		Am. Rocket Society
	Semi-Annual Progress Report, April 1, 1953		Squid Headquarters

II. PAPERS IN PROCESS OR PROSPECT

Contractor	Title and Author	Identification number	Publisher
Johns Hopkins	Turbulence in Supersonic Flow, L. S. G. Kovasznay		J. Aeronautical Sciences
Johns Hopkins	Study of the Navier-Stokes Equation in a Wave Number Space,- Chow, Tse-Sun		Rational Mechanics

Contractor	Title and Author	Identification Number	Publisher
Cornell	Wave Diagrams for Nonsteady Flow in Ducts,- G. Markstein,		Van Nostrand Co.
New York Univ.	Indicated Instantaneous Temperatures of Liquid Rocket Exhausts and Combustion Chambers,-J. H. Hett and J. B. Gilstein		J. Am. Rocket Society
Princeton	Experimental Studies of Energy Release Rates in Rocket Motors Combustion Chambers, J. V. Charyk and G. B. Matthews		J. Am. Rocket Society
Princeton	A Kinetic Study of the Diborane-Ethylene Reactions,- A. T. Whatley and R. N. Pease		J. Am. Chemical Society
Princeton	Burning Velocities of Methane with Nitrogen-Oxygen, Argon-Oxygen and Helium-Oxygen Mixtures,- W. H. Clingman, R. S. Brokaw and R. N. Pease		4th Combustion Symposium

III. PAPERS ALREADY OR TO BE PRESENTED

		Occasion
Bureau Mines	Turbulent Flame Theory Derived From Experiments	NATO - London - 19 1953

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